NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1619

AN EVALUATION OF PROPOSED REFERENCE FUEL SCALES FOR KNOCK RATING

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SUMMARY

Proposed reference-fuel scales for measuring the knocking tendencies of aviation fuels were investigated to ascertain possible limitations from consideration of sensitivity to changes of engine operating conditions and consideration of the range of knock-limited performance by which the proposed scales would extend current rating scales. The investigation was conducted entirely in F-3 and F-4 aviation fuel-rating engines.

It is concluded that the proposed reference-fuel combinations are comparable in temperature sensitivity with typical aviation fuel blends and will extend the range of knock-limited performance of current rating scales by an appreciable amount when used with satisfactory rating engines. On the other hand, difficulties with the occurrence of preignition in the F-4 engine and the severity of operating conditions in the F-3 engine indicate that these two engines in present form and under present specified operating conditions are inadequate for rating aviation fuels having performance numbers in excess of 161.

INTRODUCTION

For many years the efforts of investigators in the field of fuel research have been directed toward the development of suitable scales for measuring the knocking characteristics of fuels. As a result of these efforts, a number of scales have been studied, but only a few have passed beyond the stage of tentative acceptance. The emphasis in this development has generally been placed upon one objective – that the method permit the assignment of a numerical antiknock value to each fuel and that the rating so determined be reasonably constant regardless of the engine or operating condition used.

The achievement of this objective has been hindered because the many fuels suitable for aviation use vary widely in their

response to changes in engine conditions and also because the rating scales currently used are unsatisfactory for rating fuels in the high performance range. As a result of these difficulties, attention has been turned in recent years to the problem of establishing a rating scale that will permit determination of ratings for high-performance fuels. An effort has been made in these studies to select reference fuels that will respond to changes in engine conditions in a manner similar to that of service fuels.

On the basis of studies made by the Coordinating Research Council (reference 1), it has been proposed that triptane (2,2,3-trimethylbutane) and n-heptane be adopted as the reference fuels for a new rating scale. Both fuels would contain 3.78 ml TEL per gallon. The studies on which this proposal was based were conducted in F-3 and F-4 fuel rating engines at standard operating conditions. In order to extend the data of the Coordinating Research Council beyond the standard operating conditions used, an investigation of the proposed rating scale over a range of engine conditions was conducted at the NACA Cleveland laboratory. The results are compared with those obtained for current rating scales and other proposed scales.

In the NACA investigation reported, the effects of varying engine conditions were simulated by varying inlet-air temperature from 100° to 300° F in the F-4 engine. The combinations of reference fuels investigated were:

(1) Isooctane and n-heptane

(2) Isooctane and tetraethyl lead (0 to 6 ml/gal)

(3) Isooctane and n-heptane (both containing 3.78 ml TEL/gal)

(4) Triptane and n-heptane (both containing 3.78 ml TEL/gal)

(5) Triptane and isooctane (both containing 3.78 ml TEL/gal)

In addition to the presentation and discussion of results obtained, a brief history of rating-scale development is included as an indication of the limitations of these scales. A more detailed history is presented in reference 1.

DEVELOPMENT OF FUEL-RATING SCALES

Octane scale. - One of the earliest and the most enduring knock-rating scales is the familiar octane-number scale proposed

by Edgar in 1927 (reference 2). This scale is based on two reference fuels, isooctane (2,2,4-trimethylpentane) and n-heptane, suggested by Edgar because isooctane knocked less and n-heptane more than any fuels then known. In this system, isooctane is arbitrarily assigned a rating (octane number) of 100 and n-heptane, a rating of 0. The characteristic shape of curves representing the octane scale is shown in figure 1 from data obtained in the F-4 engine.

It can be seen that the octane scale is restricted to the determination of ratings for fuels producing knock-limited power equal to or less than that of isooctane and equal to or greater than that of n-heptane. At the lower end of the scale, the limitation offers no serious obstacle because interest in fuels with greater knocking tendencies than n-heptane is purely academic. On the other hand, the upper or isooctane end of the scale offers a very serious obstacle inasmuch as many pure hydrocarbons and commercial blending stocks are known to exceed the knock-limited power output of isooctane.

In addition to being limited in use to fuels having antiknock values between those of n-heptane and isooctane, the octane scale fails to provide numerical ratings that remain constant from engine to engine or from one condition to another. That is, a fuel having an octane number of 80 in one engine may have an octane number of 90 in another engine. Investigation has shown (reference 3), however, that the ratings of paraffinic fuels, with the exception of certain highly branched isomers, tend to remain more nearly constant from engine to engine than do widely different types of hydrocarbons within the range of performance covered by the octane scale. This fact can be attributed to the differences in sensitivities of various fuels to changes of operating conditions. Inasmuch as the rating fuels (isooctane and n-heptane) are paraffinic, it would be expected that these fuels would respond to changes in operating conditions in much the same manner as a paraffinic test fuel. If, on the other hand, the test fuel contains large concentrations of aromatic, cycloparaffinic, or olefinic compounds, the response to variations in operating conditions would differ greatly from the behavior of the paraffinic rating fuels.

Lead scale. - When fuels with knock ratings that exceeded the upper limit of the octane scale began to appear in service, it became apparent that the octane scale was no longer adequate for rating aviation fuels; consequently, the search began for a performance scale that would accommodate the high-performance fuels used in modern

aircraft power plants. In order to meet this problem, it was decided that fuels exceeding the performance of isooctane should be matched against isooctane to which had been added a given amount of tetraethyl lead. (See fig. 2.) The procedure for rating fuels by the lead scale is the same as that used for the octane scale; that is, the knock intensity of the test fuel is determined in a standard engine at standard conditions and the knocking tendencies of blends of isooctane and tetraethyl lead are compared with those of the test fuel until one blend is found to give a knock intensity equal to that of the test fuel.

Performance-number scale. - Neither the octane scale nor the lead scale permitted the assignment of a numerical rating indicative of the power output of a fuel, and in an effort to circumvent this difficulty a scale of performance numbers was adopted. The performance scale (fig. 3) represents an approximate average of the knock-limited performance as determined in several different engines at different operating conditions for isooctane containing various amounts of tetraethyl lead. Although empirically determined, this scale has proved useful in expressing fuel ratings and in correlating performance of fuels in different engines but still does not provide an absolute measure of power output.

The performance-number scale does not alter the procedure for rating fuels by use of leaded isooctane (lead scale) but does change the method of reporting the rating. For example, if a test fuel is found to give performance equal to isooctane plus 2.0 ml TEL per gallon, its rating is reported as 138 performance number. (See fig. 3.)

The performance scale as originally adopted was intended for use only with fuels having ratings above an octane number of 100 by the F-4 method. General acceptance of the scale soon led to expression of F-3 ratings by the same method and later resulted in extension of the scale below a performance number of 100.

Proposed rating scales. - One limitation of the octane scale and the lead scale is the fact that the service fuels containing an approximately constant amount of tetraethyl lead (3.0 to 4.6 ml/gal) must be matched against unleaded rating fuels or against rating fuels having variable concentrations of lead. This limitation is inherently related to the problem of fuel sensitivity to changes in operating conditions in that tetraethyl lead affects the sensitivity of the fuel to which it is added.

In order to minimize this effect on fuel ratings, investigators in the field have proposed rating scales in which the reference fuels

contain a constant amount of tetraethyl lead in the range of concentrations found in service fuels. Some of these schemes recommend the addition of a third component in the reference fuel blend, such as an aromatic, to produce reference fuels having sensitivities more nearly equal to service fuels.

FUELS

Reference fuels. - Three reference fuels were used in setting up the knock-rating scales examined in this investigation: namely, triptane, isooctane (primary), and n-heptane (primary). The inspection properties of the triptane used are presented in table I.

Service fuels. - The following service and service-type fuels were included in this investigation as a means of comparing the merits of the several rating scales:

Fuel	Nominal performance grade F-3/F-4
AN-F-26	76/88
AN-F-28 (28-R)	100/130
Special blend number 1 (SB-1) (23 percent benzene + 34 percent virgin base stock + 43 percent alkylate + 4 ml TEL/gal)	100/140
AN-F-33 (33-R)	115/145
Special blend number 2 (SB-2) (43 percent diisopropyl + 12 percent virgin base stock + 45 percent alkylate + 4 ml TEL/gal)	120/150
Special blend number 3 (SB-3) (34 percent diisopropyl + 12.5 percent hot-acid octane + 41.5 percent alkylate + 12 percent isopentane + 4 ml TEL/gal)	130/160
Special blend number 4 (SB-4) (55 percent diisopropyl + 8 percent triptane + 29 percent alkylate + 8 percent isopentane + 4 ml TEL/gal)	135/175
Special blend number 5 (SB-5) (62 percent diisopropyl + 19 percent triptane + 11 percent alkylate + 8 percent isopentane + 4 ml TEL/gal)	140/200
RAFD-52 (45 percent S reference fuel + 45 percent diisopropyl + 10 percent isopentane + 4.6 ml TEL/gal)	146/175
RAFD-53 (45 percent S reference fuel + 45 percent triptane + 10 percent isopentane + 4.6 ml TEL/gal)	153/192

In choosing these particular fuels and blends, an effort was made to cover a wide range of performance numbers both rich and lean. Inspection properties for the foregoing fuels are presented in table II.

APPARATUS AND PROCEDURE

The experimental portion of this investigation was conducted in the F-3 (CRC F-3-544; ASTM D 614) and F-4 (CRC F-4-443) rating engines. The F-3 engine was provided with a barometrically controlled dry-air supply instead of a dehydrating ice tower. The F-4 engine was equipped with a 106360D piston instead of the standard 106360G piston.

In the selection of the correct knock intensity by the F-4 method, audible knocking was accepted as the criterion. The degree of audibility was such that the operator could reproduce the point of knock with reasonable accuracy.

Complete mixture-response curves were obtained for all reference fuels and service-type blends at inlet-air temperatures of 100°, 150°, 225°, 250°, and 300° F in the F-4 engine. All other operating conditions were standard. Tests in the F-3 engine were made at standard conditions.

In order to check the reproducibility of data obtained in the F-4 engine, unleaded S reference fuel was run frequently throughout the investigation at standard conditions.

PRESENTATION OF DATA

Reproducibility of test data. - During the 7 months devoted to this investigation, the knock-limited performance of unleaded S reference fuel was determined 27 times in the F-4 engine at standard operating conditions in order to obtain an indication of the reproducibility of the data. The spread in knock-limited indicated mean effective pressures occurring in these tests is shown by the broken lines in figure 4.

For comparison the solid curve representing S reference fuel from the standard F-4 reference fuel framework is included. The deviation of the lower limit of spread from the standard curve is as great as 15 pounds per square inch at fuel-air ratios of 0.09 and 0.10; however, the exclusion of one of the 27 runs on S reference fuel would move the lower limit upward by 4 to 6 pounds per square inch at fuel-air ratios between 0.085 and 0.112.

F-4 engine data. - Where possible, complete knock-limited mixture-response curves were obtained in the F-4 engine; however, the analysis of results presented is restricted to two fuel-air ratios, 0.065 and 0.11. Data at these two fuel-air ratios and different inlet-air temperatures for the five reference-fuel combinations listed in the INTRODUCTION are presented in figures 5 to 9. The points on the curves in these figures are cross-plotted from mixture-response curves and are shown merely as an indication of the reliability of the data.

The data in figure 6(a) for inlet-air temperatures of 225° , 250° , and 300° F are incomplete, which is also true of the data at 250° F in figure 6(b). These omissions occurred because incomplete mixture-response curves were obtained in a few cases. Reruns were not made because it is believed that the omissions have a negligible effect on the value of this analysis. The data in figures 8 and 9 are also incomplete for reasons that will be subsequently given.

From figures 5 to 9 points were taken from the faired curves and replotted as shown in figures 10 to 14 for convenience in assigning ratings to service-type fuels.

F-3 engine data. - Ratings made by the F-3 method for various reference-fuel blends are presented in table III.

DISCUSSION OF RESULTS

Comparisons among various reference scales. - In figure 15, the various reference scales are compared at standard F-3 and F-4 operating conditions. It is seen in figure 15(a) that for F-3 conditions the data for leaded blends of isooctane and *n*-heptane fall on a 45-degree line indicating that the F-3 rating of isooctane containing 3.78 ml TEL per gallon is equal to that of triptane containing the same quantity of tetraethyl lead. On the other hand, data at F-4 (rich) conditions (fig. 15(b)) show that for equal knock-limited indicated mean effective pressures more isooctane is required than triptane in leaded blends with *n*-heptane. Figure 15(b) indicated that between 80 and 84 percent triptane in a blend with *n*-heptane (leaded) would be required to equal the upper limit (161) of the current performance scale.

An additional observation can be made from figure 15; namely that for F-3 conditions the two-component reference-fuel systems with constant tetraethyl-lead concentrations are related by straight lines, whereas at F-4 conditions definite curvature is obtained.

Unpublished data from the Coordinating Research Council were compared with the NACA data in figure 15 and the agreement was found to be quite good.

Temperature sensitivity of reference fuels. - As a measure of the temperature sensitivity of the reference-fuel combinations, the slopes of the curves shown in figures 5, 6, 7, 8, and 9 were computed at an inlet-air temperature of 225° F (standard F-4 conditions) and plotted against the knock-limited indicated mean effective pressures at the same temperature. These plots were made for fuel-air ratios of 0.065 and 0.11 and are shown in figure 16. A single curve was drawn through each set of points (lean and rich) to illustrate the variation of temperature sensitivity with knock-limited performance for the various reference-fuel blends. The different portions of the curve determined by individual reference-fuel combinations are also indicated on this figure.

It is seen in figure 16 that above the upper limit of the current performance-number scale the sensitivity increases rapidly as the knock-limited indicated mean effective pressure increases. If this trend is generally true for service-type fuels, then it is apparent from figure 16 that such fuels having high knock limits should be matched against leaded blends of triptane and isooctane or triptane and n-heptane in order to have reference fuels and service fuels of comparable sensitivity. For lower performance fuels, however, any of the reference scales indicated would be suitable from sensitivity considerations.

Temperature sensitivity of service-type fuels. - The effects of inlet-air temperature on the knock-limited performance of 10 service-type fuels were investigated in the F-4 engine. The results are presented in figure 17. In order to compare the temperature sensitivities for the service-type fuels with the sensitivities of the reference fuels, the slopes of the curves (at 225° F) were determined from figure 17 and plotted as shown in figure 18. On this same figure the curves from figure 16 were reproduced.

It is seen in figure 18 that the points representing service fuels lie primarily above the curves established for the reference fuels. This divergence is attributed to the fact that the service fuels are blends containing a number of different components; whereas the reference-fuel blends are composed of only two components. Insofar as a perfect rating scale is concerned, the ideal condition would be for the service-fuel data to fall directly on the reference-fuel curve.

Because this situation is improbable, the next best solution must be for reference-fuel blends and service fuels to have sensitivities of approximately the same magnitude at the same knock-limited performance levels. The attainment of this characteristic can be approached by the use of either the joint reference scale, leaded triptane-isooctane and leaded isooctane – *n*-heptane, or by the leaded triptane – *n*-heptane scale (fig. 18).

In evaluating the merits of a rating scale, however, three factors other than temperature sensitivity must be considered, namely, that the scale

(1) should be a continuous scale

(2) should involve a minimum number of reference fuels

(3) should cover the complete range of knock-limited performance likely to be encountered with a variety of service fuels

In figures 16 and 18, it has been shown that both the leaded triptane – *n*-heptane scale and the joint scale of leaded isooctane – *n*-heptane and leaded triptane-isooctane have the last of these characteristics. Only the leaded triptane – *n*-heptane scale, however, possesses the first two characteristics as well; consequently, this scale appears to be the most practical choice. The problem of availability of reference fuels is obviously important but is beyond the scope of this investigation.

Ratings of service-type fuels. - The 10 service-type fuels were assigned ratings in terms of the five reference scales examined in this investigation. These ratings are given in table IV for standard F-3 conditions and for F-4 conditions at five inlet-air temperatures and two fuel-air ratios. Figures 10 to 14 were used for assignment of the F-4 ratings.

The ratings in table IV were made for the purpose of comparing the constancy of the assigned ratings over a range of conditions established by varying inlet-air temperature. This comparison is presented in figures 19 and 20. On the ordinates of the (b) parts of these figures the scales are discontinuous. This arrangement was chosen inasmuch as the leaded isooctane – *n*-heptane scale and the leaded triptane-isooctane scales are considered for joint use. The broken-line portions of curves in figures 19(b) and 20(b) indicate that such fuels would be matched against different pairs of reference fuels depending upon the operating conditions.

Figures 19 and 20 are included merely to illustrate the constancy of numerical ratings and cannot alone serve as a basis

for choosing the best reference scale. This statement is based on the fact that the constancy of an assigned rating from one set of operating conditions to another is largely dependent upon the relative sensitivities of reference fuels and test fuels previously discussed.

Limitations of reference scales. - In the preceding discussion, it has been stated that in many cases knock-limited indicated mean effective pressures were not obtained for some of the higher-performance service-type and reference fuels investigated in the F-4 engine. The attainment of complete data for high-performance fuels was hampered throughout the investigation by the tendency of these fuels to preignite in the F-4 engine. The engine operator at all times obtained as much of the mixture-response curve as possible before the start of preignition; however, for some fuels points richer than about 0.08 fuel-air ratio could not be taken. Inasmuch as the peaks of the curves were not obtained, ratings could not be made in the fuel-air-ratio range characteristic of the standard F-4 rating method.

Preignition occurred with the high-performance fuels regardless of the condition of the engine and changing the type of spark plug failed to prevent preignition.

Preignition was encountered so frequently that earlier unpublished data obtained at this laboratory were examined in order to define the range of indicated mean effective pressure in which preignition is likely to occur in the F-4 engine. The results of this study are presented in figure 21 together with data from the present investigation. Each point on this plot represents the richest point of a mixture-response curve that could be obtained before the occurrence of preignition. It is seen in this figure that with several fuels it was possible to reach preignition-free performance at indicated mean effective pressures greater than 400 pounds per square inch; however, a number of fuels preignited at levels below 400 down to about 258 pounds per square inch. In most cases, the limiting fuel-air ratios were leaner than the fuel-air ratio range in which F-4 ratings are usually made.

Inasmuch as preignition imposes a very real limit on an F-4 rating scale at a rich fuel-air ratio, the maximum indicated mean effective pressures that can be obtained with current and proposed reference scales are indicated in figure 21. The difference between scales is about 75 pounds per square inch indicated mean effective pressure, thus the adoption of either reference scale utilizing triptane as one of the components will extend the range in which "direct match" ratings can be made by about 75 pounds per square inch. Even then there will be some fuels (as indicated by preignition test points in fig. 21) that cannot be rated in this

range. In fact only three of the five service-type fuels exceeding a performance number of 161 could be rated in the present investigation (shown as solid lines between fuel-air ratios of 0.10 and 0.12 in figure 21.) The remaining two fuels having performance numbers over 161 preignited at fuel-air ratios leaner than 0.08. (Indicated on fig. 21 by □).

CONCLUSIONS

Considering the general implications of the investigation reported herein, it is clear than if F-3 and F-4 engines are to be used as the standard fuel-rating engines, the advantages to be gained by the adoption of new reference-fuel systems utilizing triptane are questionable. It has been shown that the present scale of performance numbers will permit ratings for fuels up to a performance number of 161 in the F-3 engine and that triptane plus 3.78 ml TEL per gallon, which represents the maximum performance of either of the proposed reference-fuel combinations, will permit ratings only up to a performance number of 151. Moreover, in the F-4 engine the tendencies of many high-performance service-type fuels and high-performance reference-fuel blends to preignite makes the advantage of extending the range in which ratings can be made in this engine somewhat uncertain.

If, however, it is assumed that new rating engines will be developed in the future to replace the F-3 and F-4 engines, the conclusions in this study may be reduced to pure considerations of the reference fuels. On this basis, the following conclusions are drawn and these conclusions are necessarily confined to the conditions used in this investigation:

1. At rich mixtures (F-4 method) the use of the leaded triptane – n-heptane scale or the joint scale, leaded triptane-isooctane and leaded isooctane – n-heptane, will extend the range of performance in which ratings can be made by an indeterminate amount over the range of the current scale of performance numbers.

2. At lean mixtures (F-3 method), the evidence obtained in this investigation indicates that the proposed reference scales would reduce the range of performance that can now be measured on the scale of performance numbers.

3. Either the joint reference scale, leaded triptane-isooctane and leaded isooctane – n-heptane, or the leaded

triptane – n-heptane scale is satisfactory from considerations of sensitivity to changes of operating conditions and considerations of the range of knock-limited indicated mean effective pressures to be measured. The leaded triptane – n-heptane scale, however, is more desirable because only two reference fuels are involved and the scale itself is continuous.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 5, 1947.

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TABLE I - INSPECTION DATA FOR TRIPTANE

(2,2,3-TRIMETHYLBUTANE)

A.S.T.M. distillation	
Initial boiling point, °F	172
10 percent evaporated, °F	174
40 percent evaporated, °F	174
50 percent evaporated, °F	174
90 percent evaporated, °F	175
End point, °F	180
Residue, percent	0.4
Loss, percent	0.8
Copper dish gum, (mg/100 ml)	1.0
Reid vapor pressure, (lb/sq in.)	3.0
Freezing point, (°F)	-18
Hydrogen-carbon ratio	0.191
Net heat of combustion, (Btu/lb)	19,200
Refractive index, n_D, at 68° F	1.3896

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TABLE II - INSPECTION DATA FOR SERVICE AND SERVICE-TYPE FUELS

Fuel designation	AN-F-26	AN-F-28 (28-R)	AN-F-33 (33-R)	SB-1	SB-2	SB-3	SB-4	SB-5	RAFD-52	RAFD-53
A.S.T.M. distillation										
Initial boiling point, °F	136	104	96	122	122	106	124	122	120	140
10 percent evaporated, °F	160	145	134	136	144	134	136	136	142	168
40 percent evaporated, °F	180	192	197	148	160	160	148	144	160	188
50 percent evaporated, °F	190	209	217	152	170	170	152	148	166	190
90 percent evaporated, °F	236	278	274	224	242	240	224	180	204	200
End point, °F	320	338	349	342	350	340	342	290	236	232
Residue, percent	0.9	0.9	1.0	0.8	1.0	1.0	1.2	0.9	1.0	0.4
Loss, percent	1.1	-------	1.0	1.2	1.3	0.5	1.2	0.6	1.0	0.6
TEL content, (ml/gal)	4.95	4.36	4.53	4.02	4.17	4.39	4.11	3.96	4.52	4.69
Copper dish gum, (mg/100 ml)	6.9	2.9	5	10.1	0.8	6.3	1.5	16.6	1.1	3.3
Freezing point, (°F)	-76	-76	-76	-36.4	-76	-76	-76	-76	-76	-76
Hydrogen-carbon ratio	0.177	0.174	0.182	0.156	0.192	0.189	0.194	0.191	0.187	0.188
Net heat of combustion, (Btu/lb)	19,108	18,700	18,900	18,517	19,196	19,155	19,380	19,286	19,247	19,378

TABLE III - F-3 RATINGS FOR REFERENCE-FUEL BLENDS

Composition, percent by volume (a)			F-3 Rating	
n-Heptane	Isooctane	Triptane	Octane number or isooctane + TEL	Performance number
100	0	--------	47	-----------
80	20	--------	60	-----------
60	40	--------	76.3	54
40	60	--------	85.3	65.5
20	80	--------	.14	105
0	100	--------	3.78	151.3
---------	80	20	4.0	152.5
---------	60	40	4.0	152.5
---------	40	60	4.0	152.5
---------	20	80	4.4	154.5
---------	0	100	3.6	150.5
80	---------	20	62	-----------
60	---------	40	76.8	54.5
40	---------	60	90.8	75.3
20	---------	80	.85	123

[a]All blends contained 3.78 ml TEL/gal.

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TABLE IV - F-3 AND F-4 RATINGS OF SERVICE AND SERVICE-

Fuel designation and nominal grade	Rating scale (a)	F-3 rating (b)	F-4 rating at fuel-air ratio of 0.065 (c)					F-4 rating at fuel-air ratio of 0.11 (c)				
			Inlet-air temperature, °F					Inlet-air temperature, °F				
			100°	150°	225°	250°	300°	100°	150°	225°	250°	300°
AN-F-26 (76/88)	Imep	------	134	114	94	88	79	159	163	156	152	145
	ON	91	95	94	95	95	97	97	98	98	98	98
	PN	76	85	82	85	85	90	90	93	93	93	93
	LIH	60	72	69	64	61	55	77	80	80	80	78
	LTH	60	60	58	56	55	53	63	66	66	66	65
	LTI	------	----	----	----	----	----	----	----	----	----	----
AN-F-28 (100/130)	Imep	------	180	154	121	111	92	216	214	202	195	180
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	101	112	110	110	110	109	125	130	127	125	119
	LIH	72	86	84	81	78	68	92	93	93	92	89
	LTH	72	72	71	68	67	62	75	76	75	75	73
	LTI	------	----	----	----	----	----	----	----	----	----	----
SB-1 (100/140)	Imep	------	184	148	104	95	83	231	225	212	207	193
	ON	99.3	----	----	99	99	100	----	----	----	----	----
	PN	98	114	107	97	97	100	134	136	134	133	128
	LIH	71	87	83	72	67	59	95	95	95	95	93
	LTH	71	73	69	61	59	56	78	78	77	77	75
	LTI	------	----	----	----	----	----	----	----	----	----	----
AN-F-33 (115/145)	Imep	------	229	178	137	126	107	----	229	222	218	205
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	115	138	126	120	121	122	----	138	140	140	137
	LIH	77	95	91	89	87	81	----	96	97	97	95
	LTH	77	80	76	73	72	70	----	79	79	78	77
	LTI	------	----	----	----	----	----	----	----	----	----	----
SB-2 (120/150)	Imep	------	277	212	143	131	109	260	257	249	244	231
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	121	157	148	125	125	124	148	152	155	155	152
	LIH	79	----	99	91	89	83	99	----	----	----	----
	LTH	79	----	----	75	74	70	----	----	----	----	----
	LTI	------	7	----	----	----	----	----	2	5	5	1

[a]Imep, knock-limited indicated mean effective pressure; ON, octane number; PN, performance number; LIH, blend of isooctane and *n*-heptane containing 3.78 ml TEL/gal; LTH, blend of triptane and *n*-heptane containing 3.78 ml TEL/gal; LTI, blend of triptane and isooctane containing 3.78 ml TEL/gal.

[b]Octane numbers and performance numbers obtained by the standard F-3 rating procedure. Ratings in terms of other scales estimated from figure 15(a).

[c]Knock-limited imep obtained from faired curves in figure 17. Ratings made from figures 10 to 14.

TYPE FUELS IN TERMS OF SEVERAL REFERENCE-FUEL COMBINATIONS

Fuel designation and nominal grade	Rating scale (a)	F-3 rating (b)	F-4 rating at fuel-air ratio of 0.065 (c)					F-4 rating at fuel-air ratio of 0.11 (c)				
			Inlet-air temperature, °F					Inlet-air temperature, °F				
			100°	150°	225°	250°	300°	100°	150°	225°	250°	300°
SB-3 (130/160)	Imep	------	292	235	162	143	118	270	270	265	258	235
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	134	----	156	147	139	135	152	159	----	----	155
	LIH	86	----	----	99	95	90	----	----	----	----	----
	LTH	86	----	----	79	77	74	----	----	----	----	----
	LTI	------	16	9	----	----	----	4	11	14	13	4
SB-4 (135/175)	Imep	------	----	262	189	165	126	----	----	298	286	261
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	141	----	----	----	160	146	----	----	----	----	----
	LIH	91	----	----	----	----	95	----	----	----	----	----
	LTH	91	----	----	----	----	77	----	----	----	----	----
	LTI	------	----	24	15	9	----	----	----	29	26	23
SB-5 (140/200)	Imep	------	----	267	195	173	133	----	----	----	----	299
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	143	----	----	----	----	155	----	----	----	----	----
	LIH	92	----	----	----	----	100	----	----	----	----	----
	LTH	92	----	----	----	----	80	----	----	----	----	----
	LTI	------	----	27	20	16	2	----	----	----	----	44
RAFD-52 (146/175)	Imep	------	----	247	205	188	137	----	----	287	279	262
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	147	----	160	----	----	----	----	----	----	----	----
	LIH	96	----	----	----	----	----	----	----	----	----	----
	LTH	96	----	----	----	----	----	----	----	----	----	----
	LTI	------	----	15	29	31	6	----	----	24	23	23
RAFD-53 (153/192)	Imep	------	----	----	246	189	147	----	----	----	----	312
	ON	------	----	----	----	----	----	----	----	----	----	----
	PN	147	----	----	----	----	----	----	----	----	----	----
	LIH	96	----	----	----	----	----	----	----	----	----	----
	LTH	96	----	----	----	----	----	----	----	----	----	----
	LTI	------	----	----	----	32	16	----	----	----	----	50

NACA

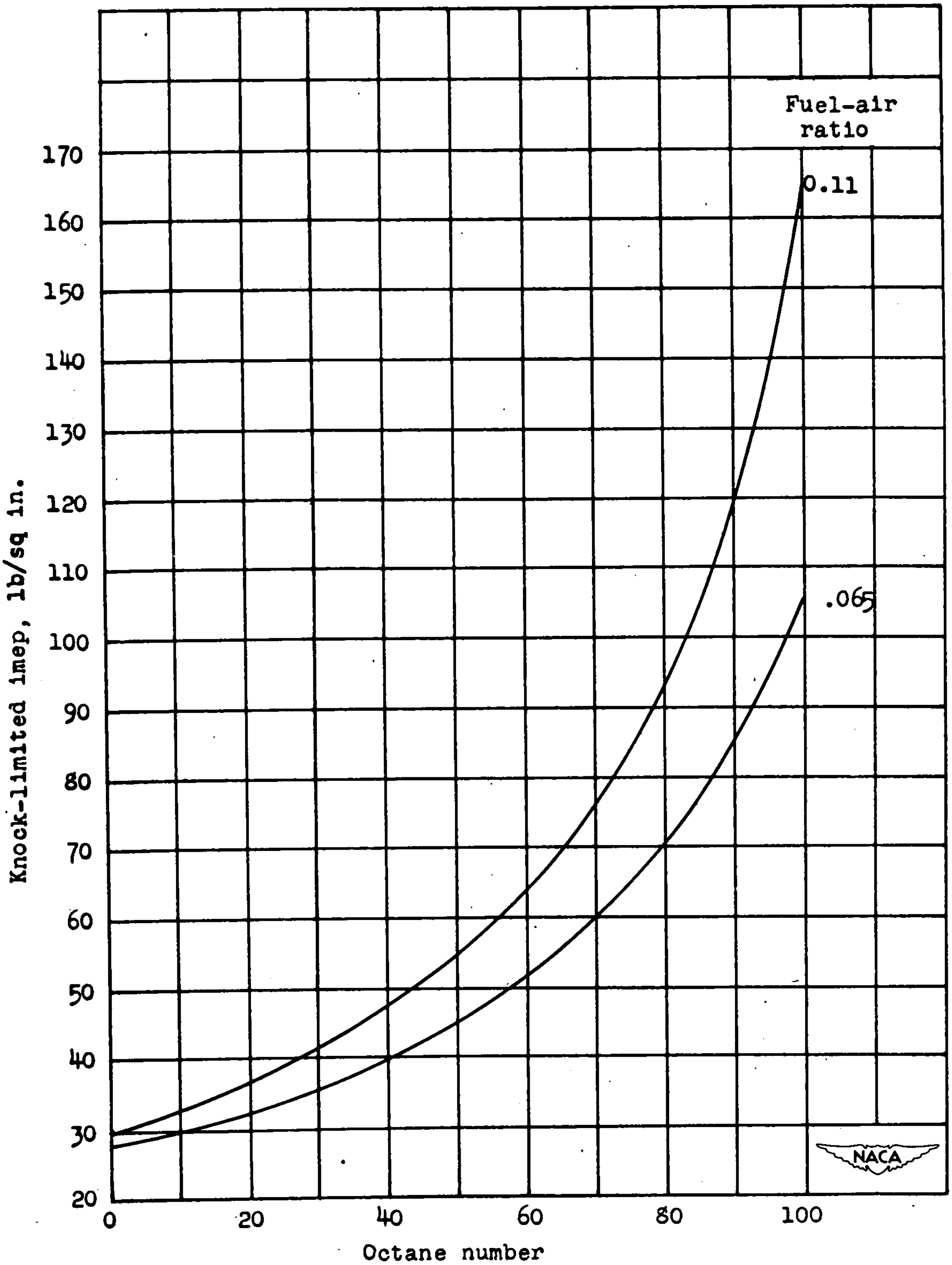


Figure 1. - Curve representing octane scale determined on F-4 engine at standard conditions.

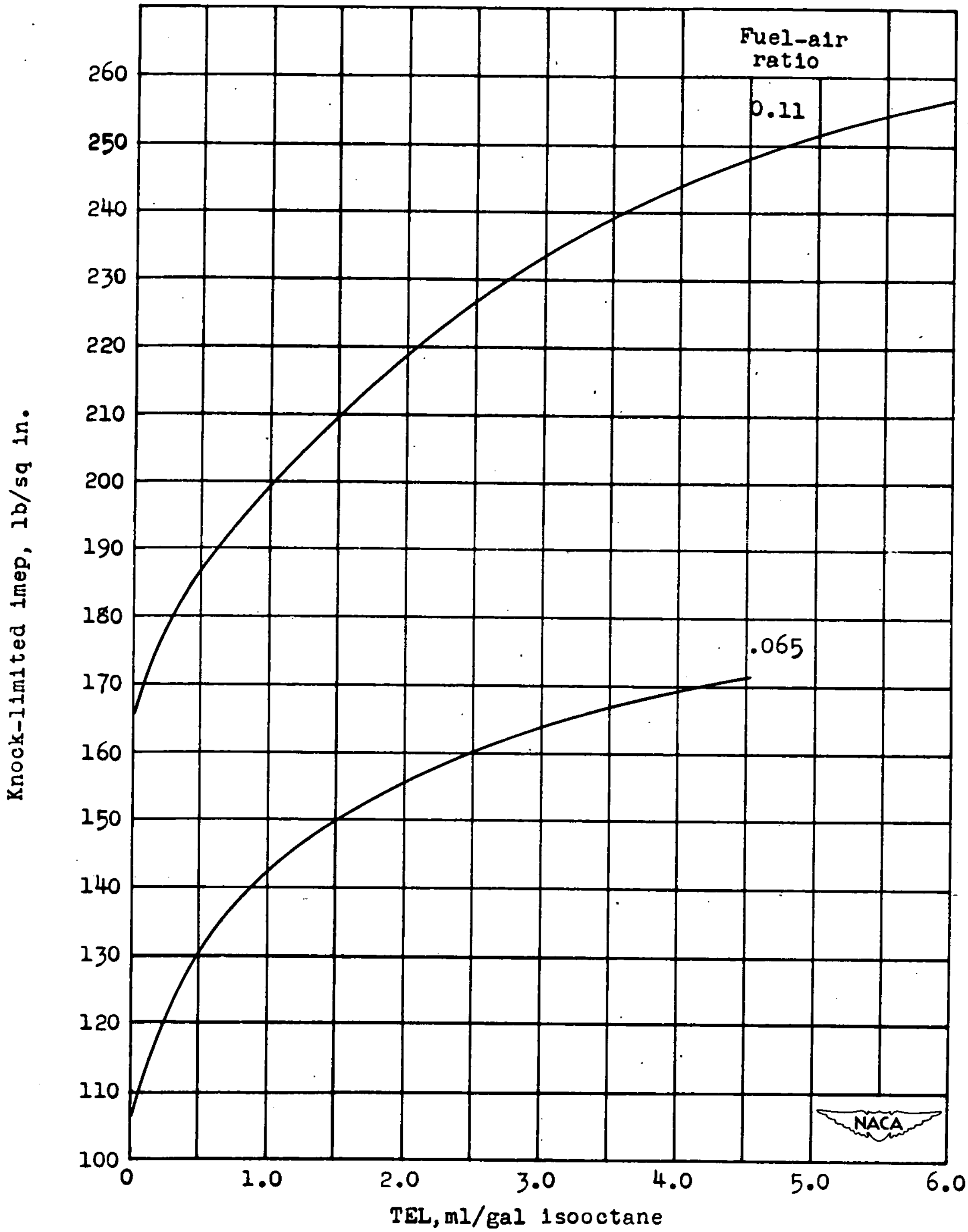


Figure 2. - Curve representing lead scale determined on F-4 engine at standard conditions.

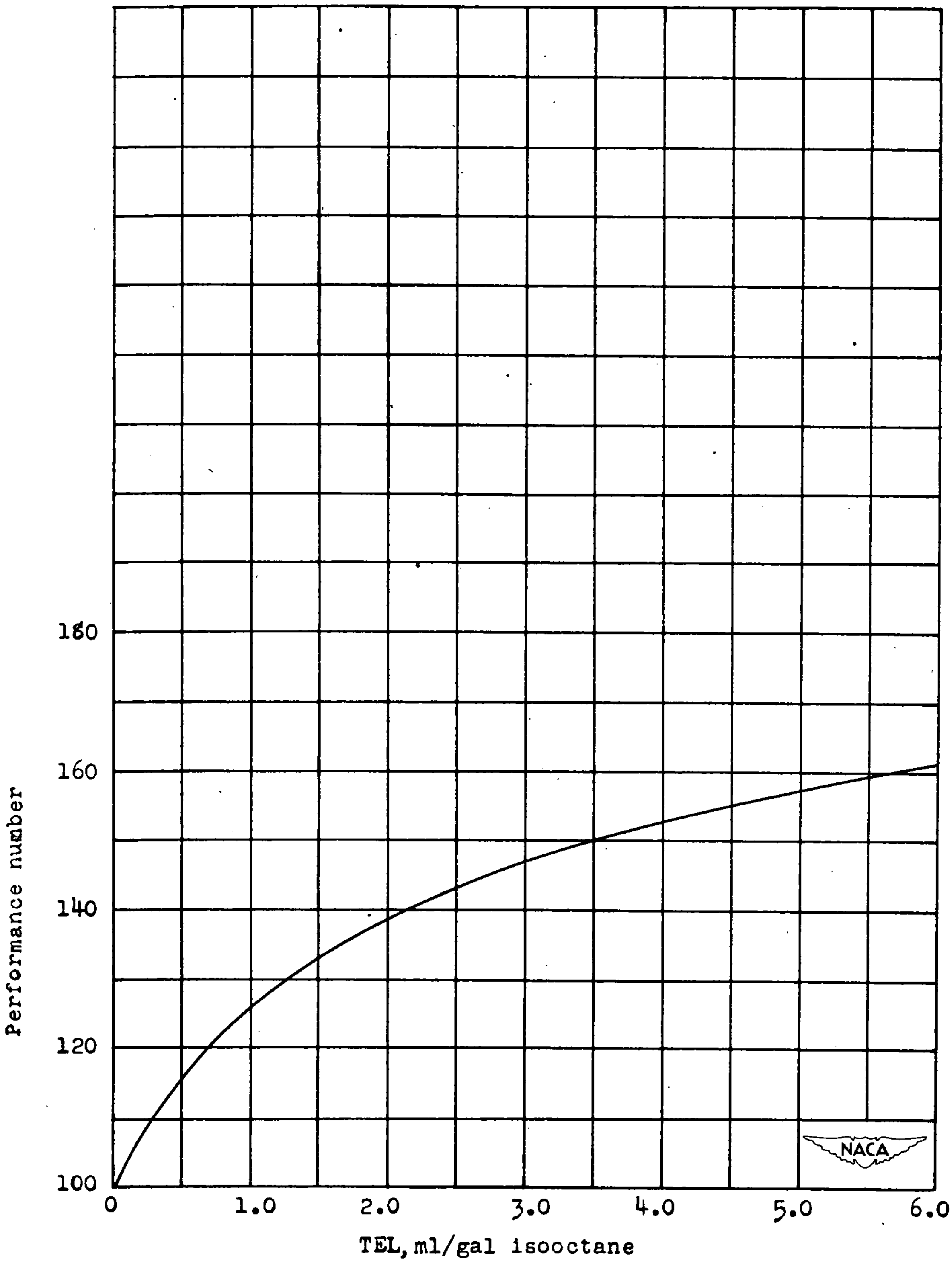


Figure 3. - Performance-number scale.

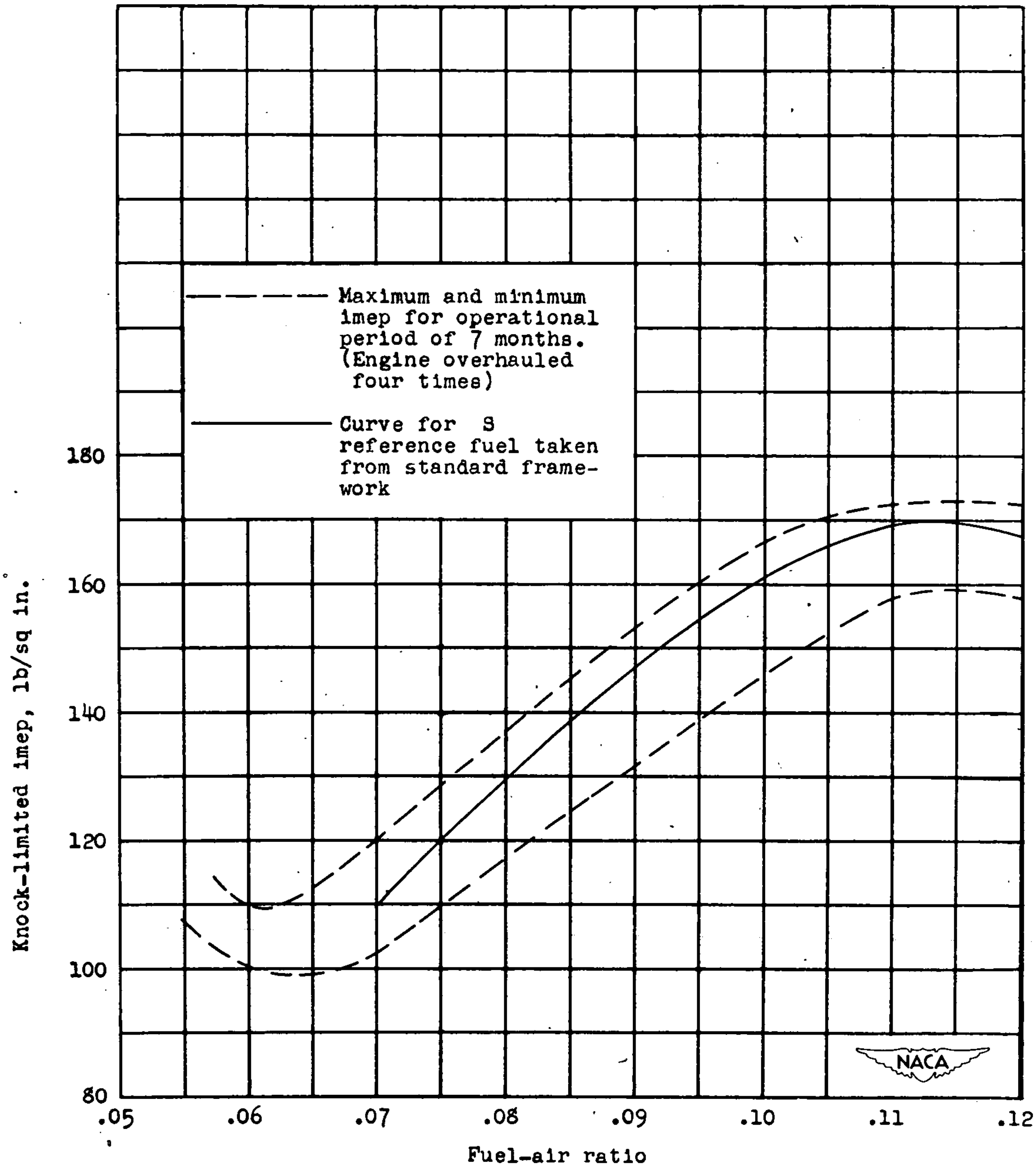
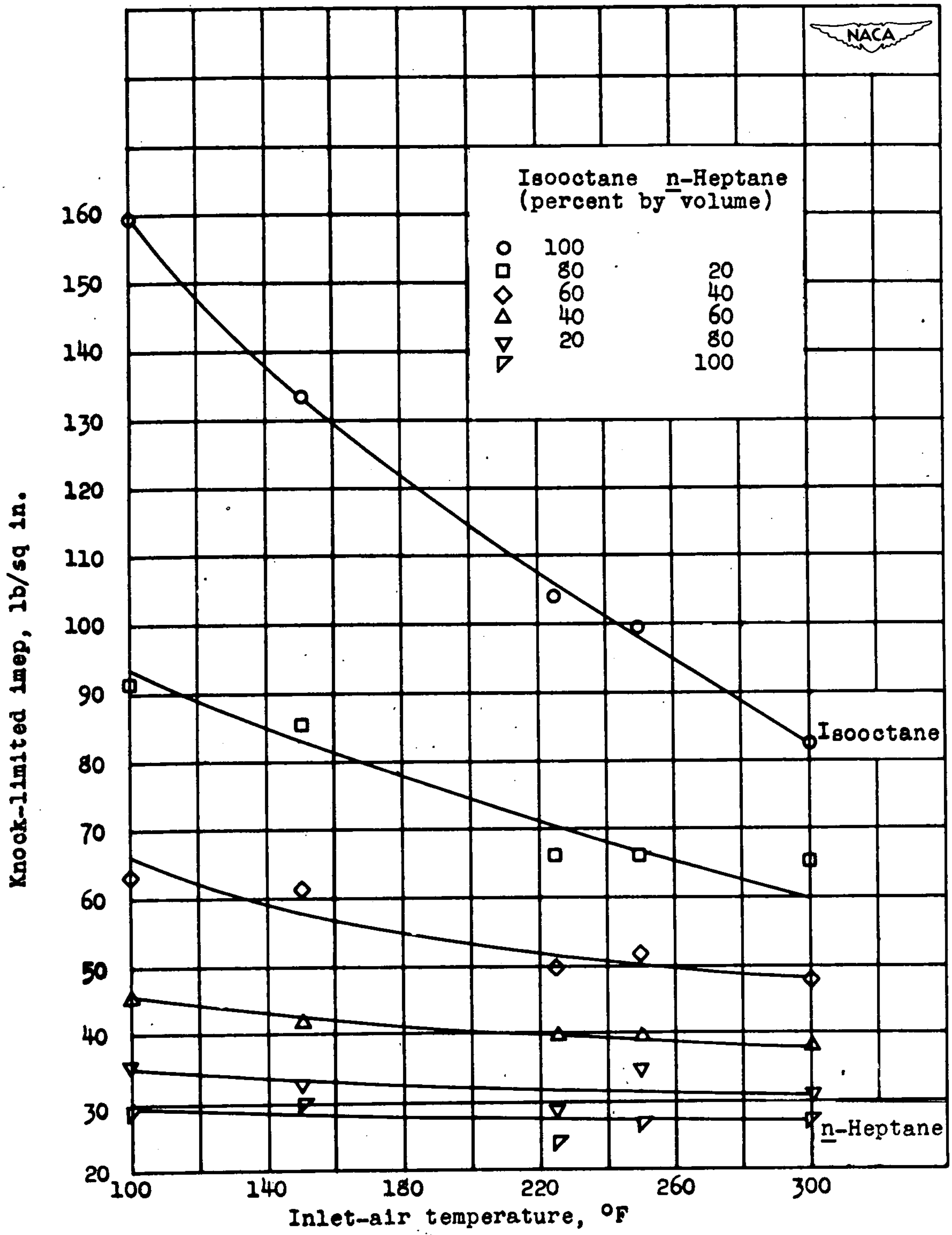
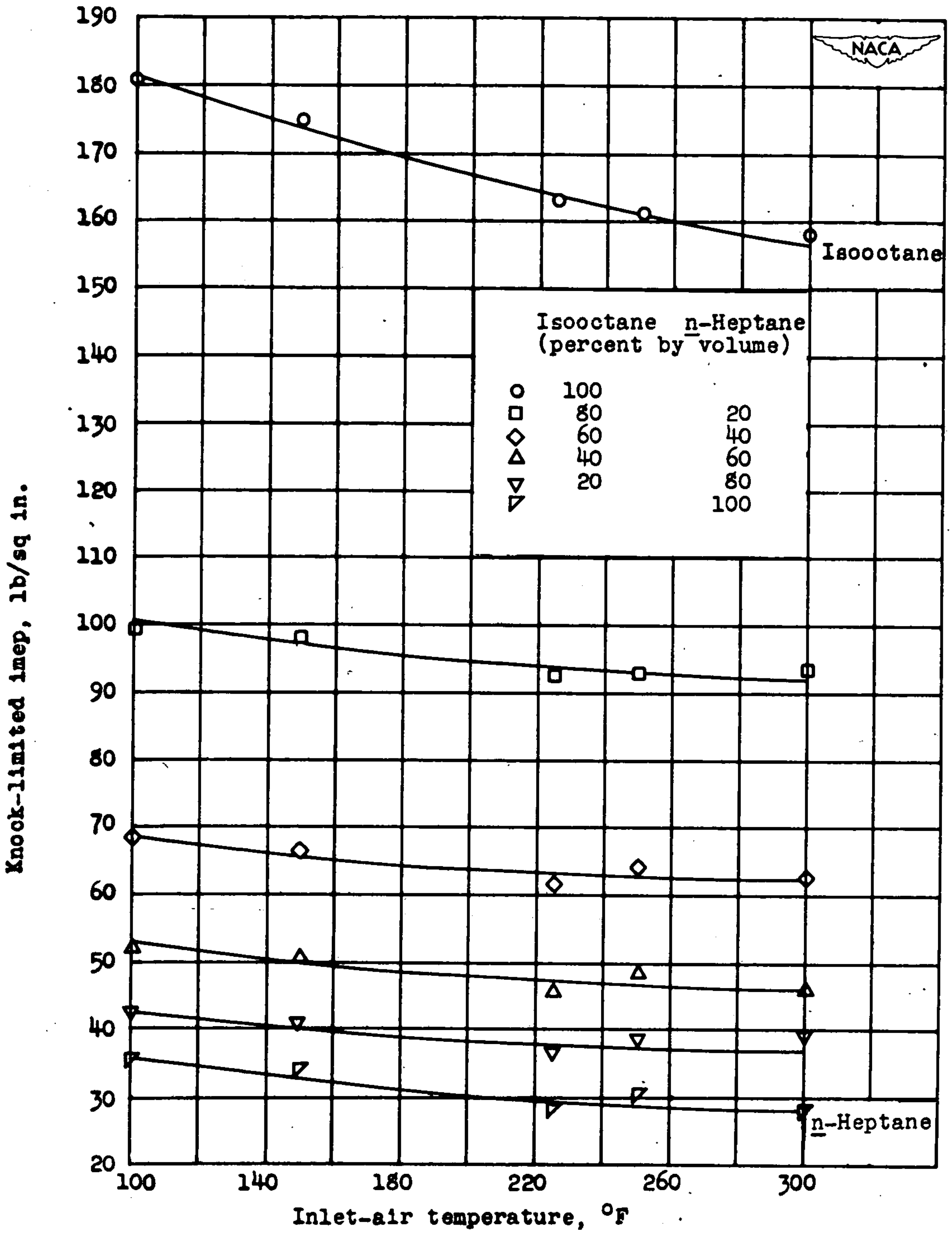


Figure 4. - Reproducibility of engine results obtained with S reference fuel in F-4 rating engine at standard operating conditions.



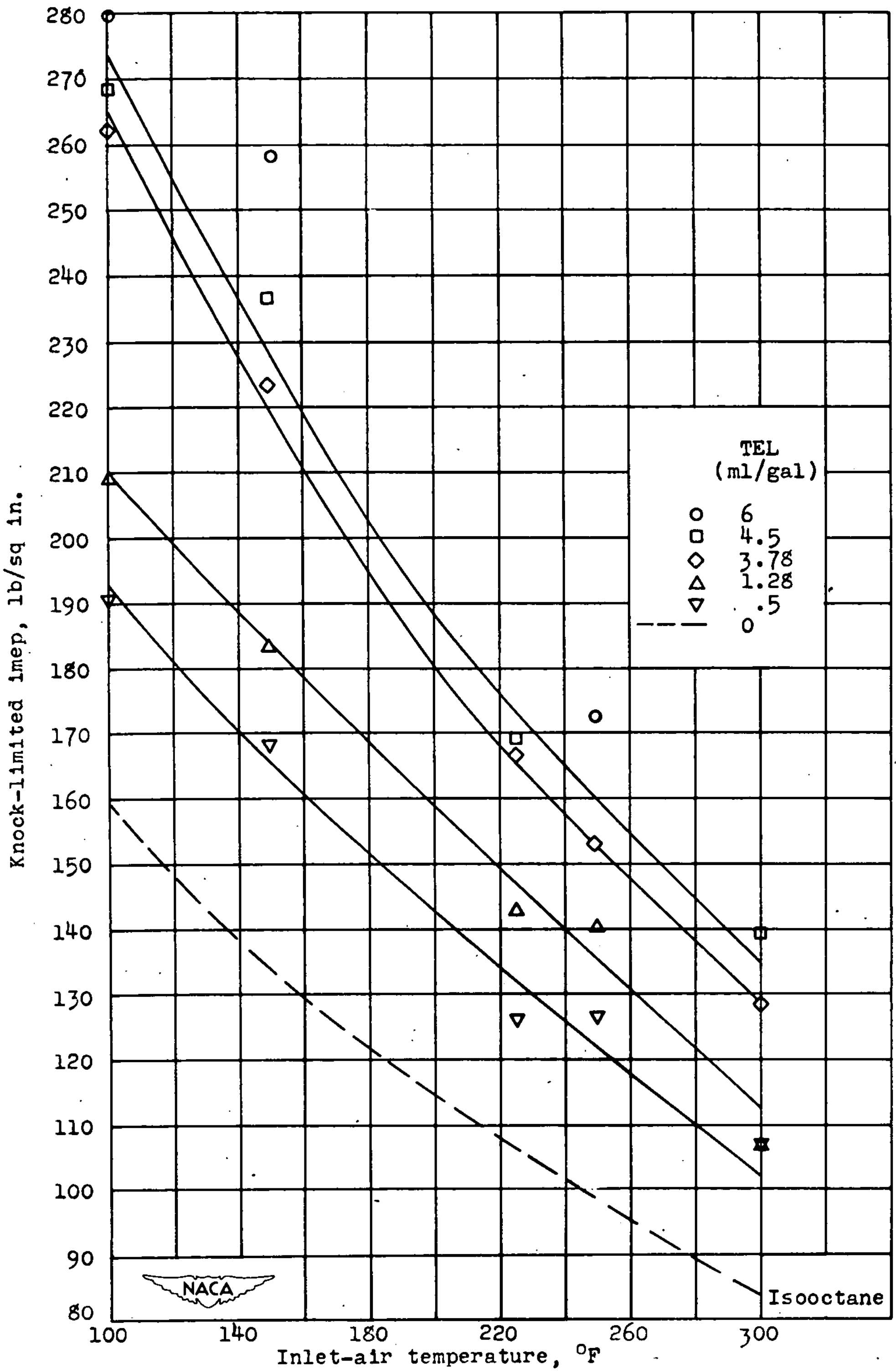
(a) Fuel-air ratio, 0.065.

Figure 5. - Knock-limited performance of unleaded blends of isooctane and n-heptane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



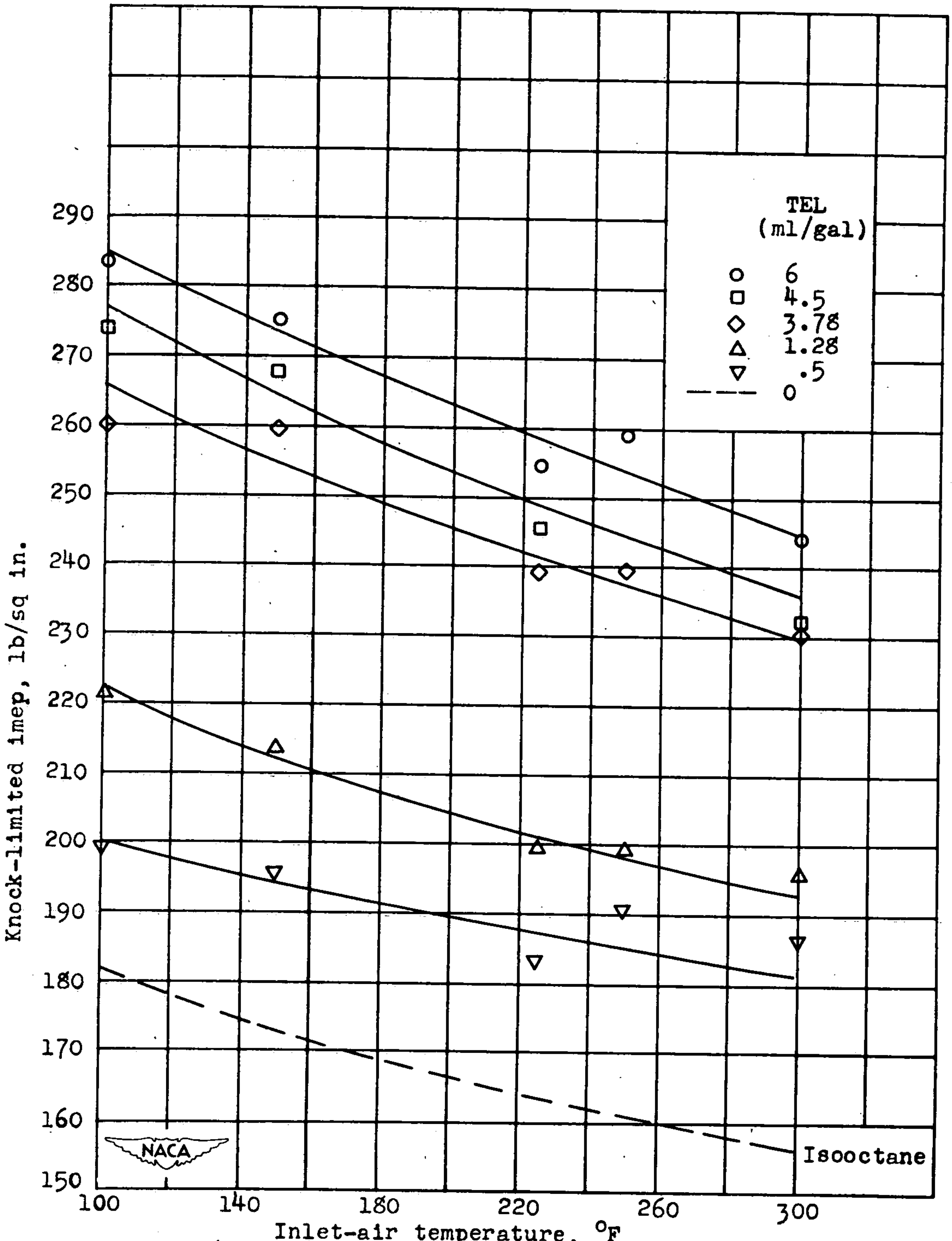
(b) Fuel-air ratio, 0.11.

Figure 5. - Concluded. Knock-limited performance of unleaded blends of isooctane and n-heptane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



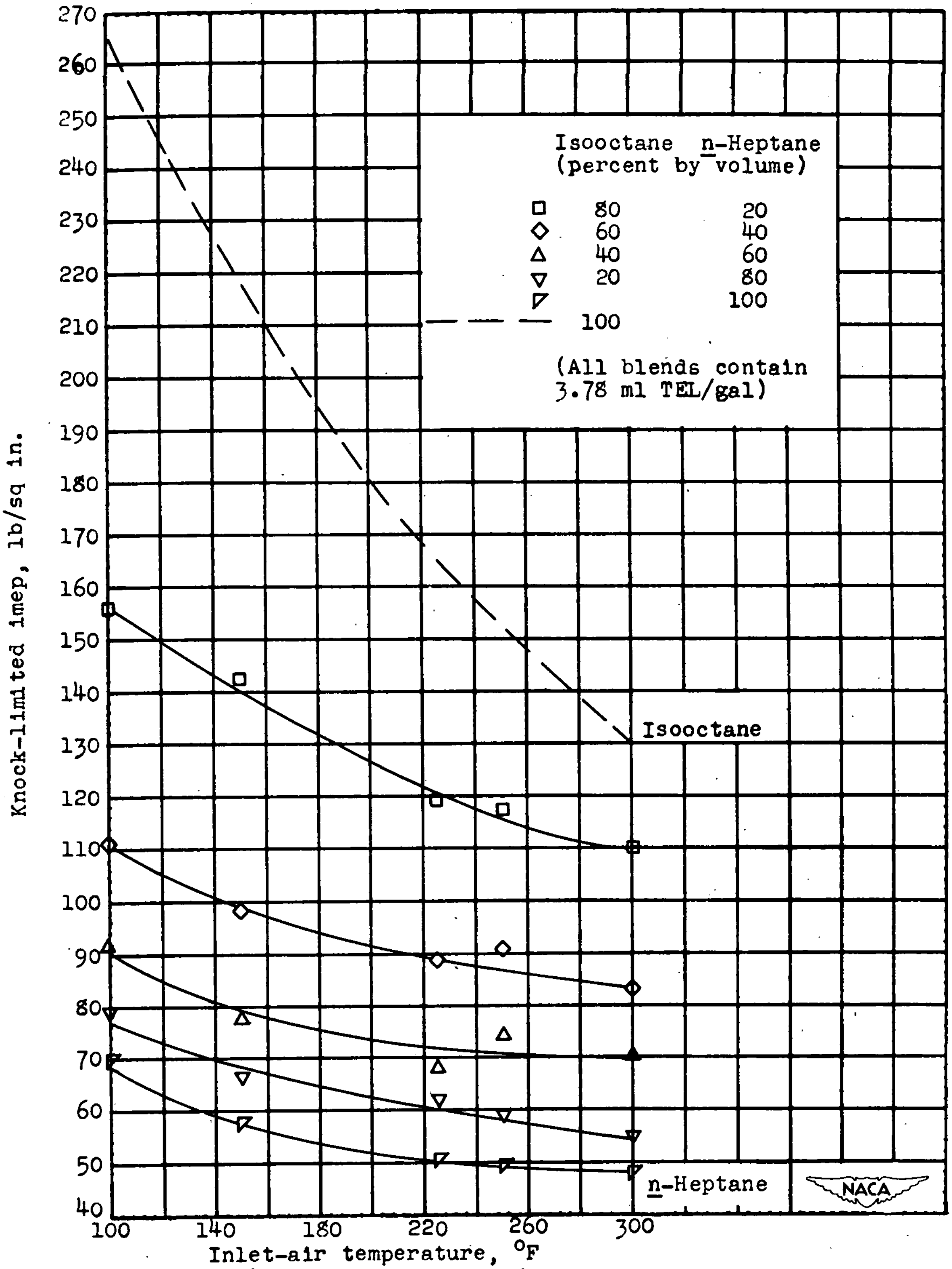
(a) Fuel-air ratio, 0.065.

Figure 6. - Knock-limited performance of isooctane containing various concentrations of tetraethyl lead at several inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



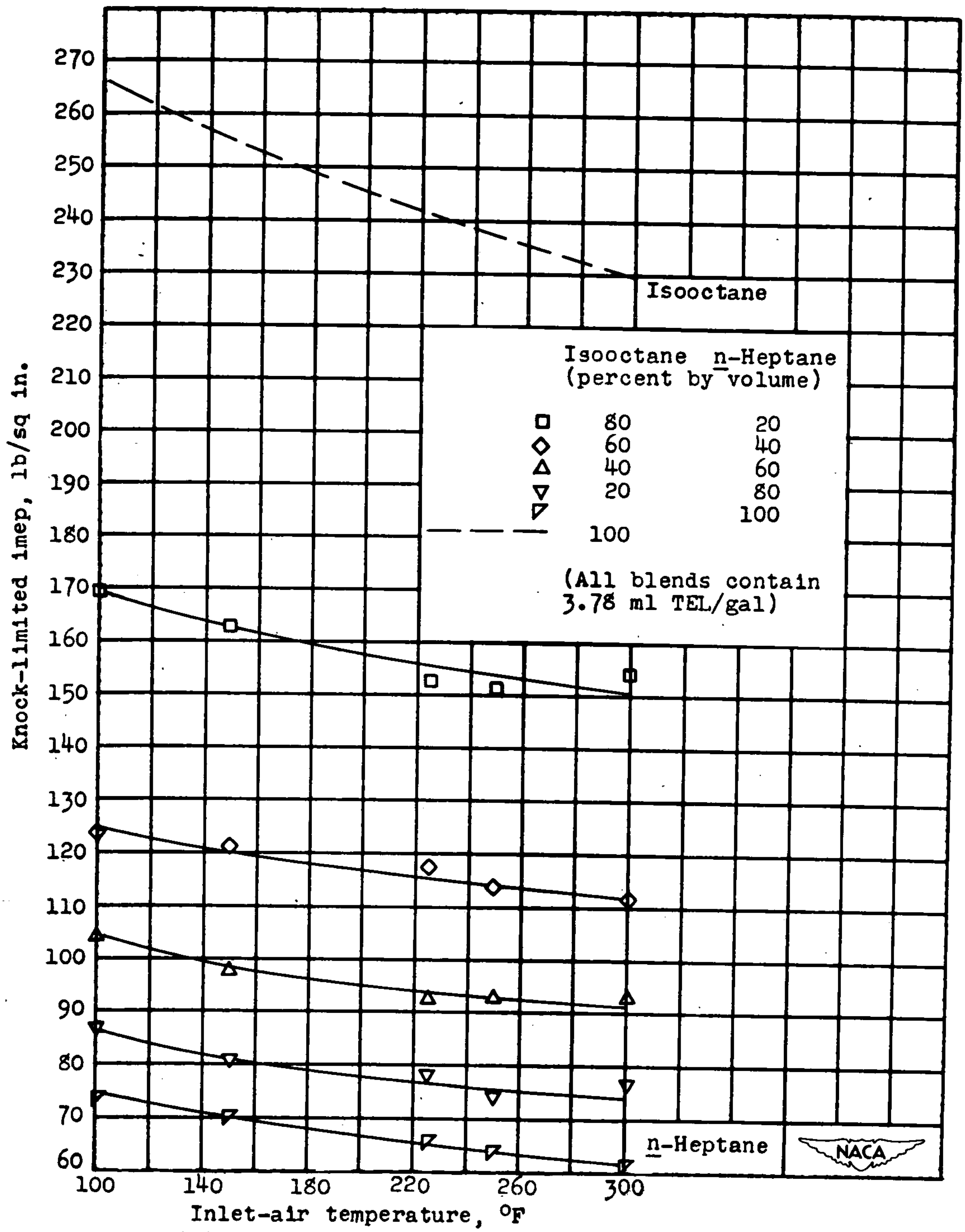
(b) Fuel-air ratio, 0.11.

Figure 6. - Concluded. Knock-limited performance of isooctane containing various concentrations of tetraethyl lead at several inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



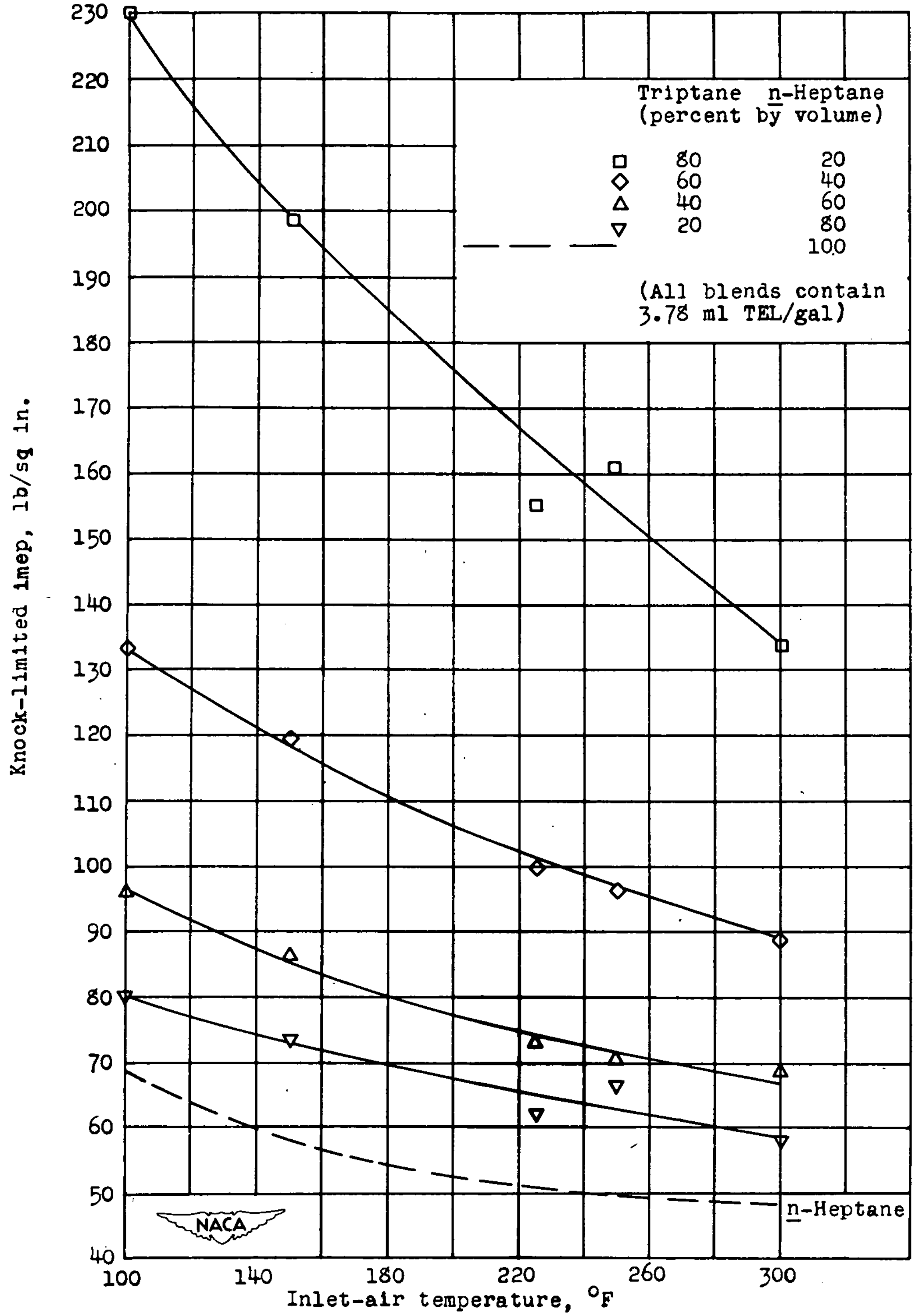
(a) Fuel-air ratio, 0.065.

Figure 7. - Knock-limited performance of leaded blends of isooctane and n-heptane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



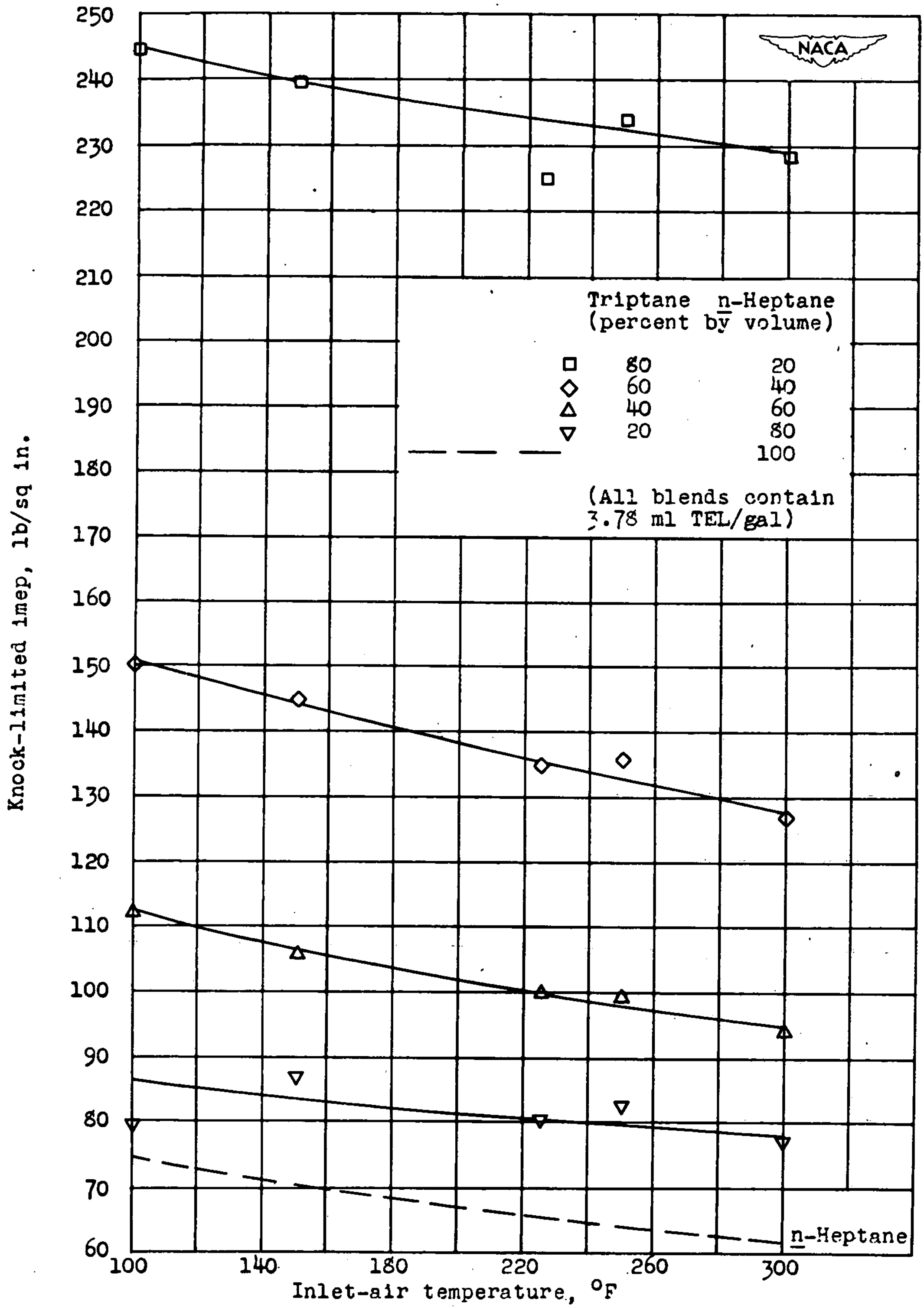
(b) Fuel-air ratio, 0.11.

Figure 7. - Concluded. Knock-limited performance of leaded blends of isooctane and n-heptane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



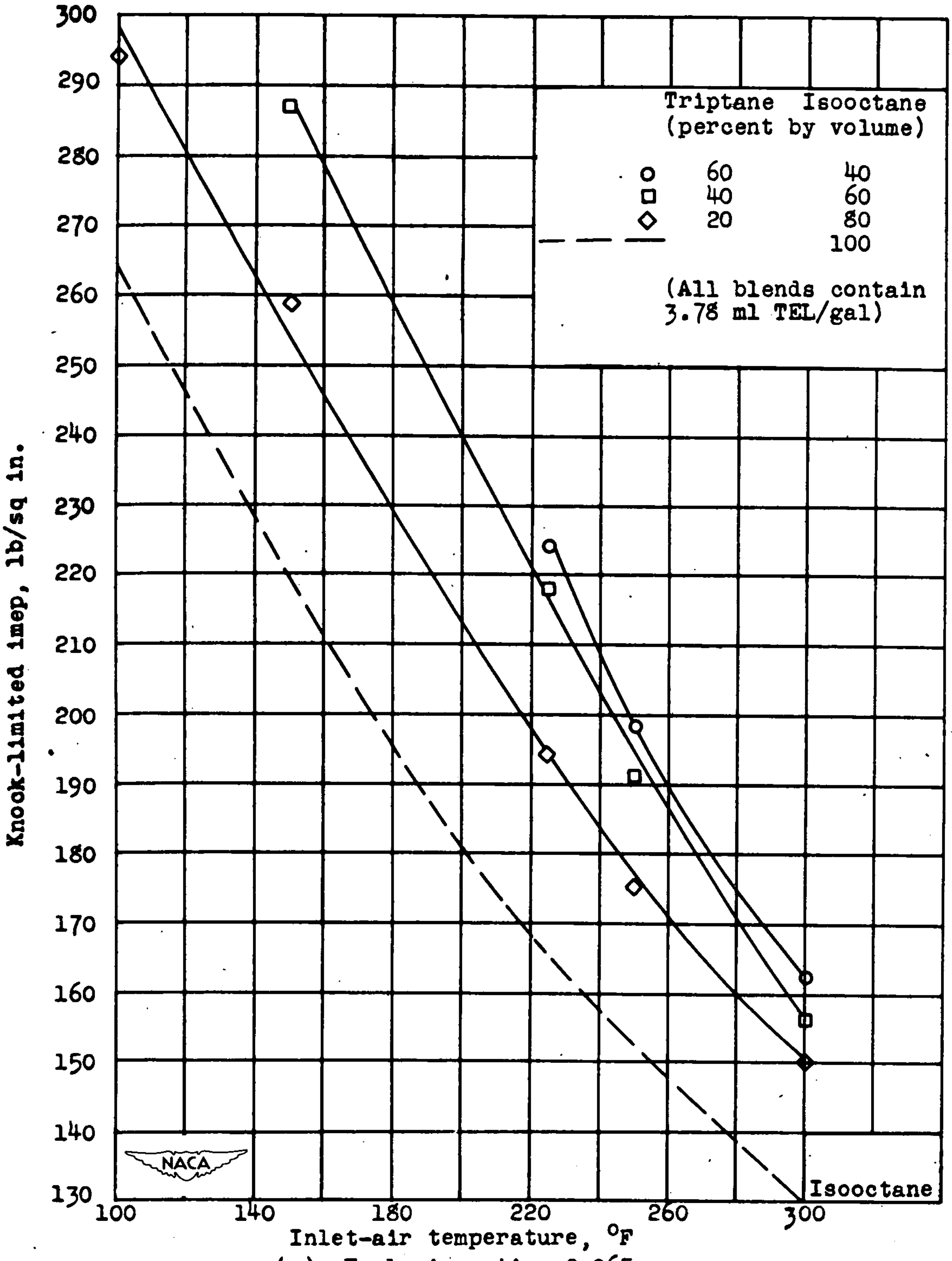
(a) Fuel-air ratio, 0.065.

Figure 8. - Knock-limited performance of leaded blends of triptane and n-heptane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



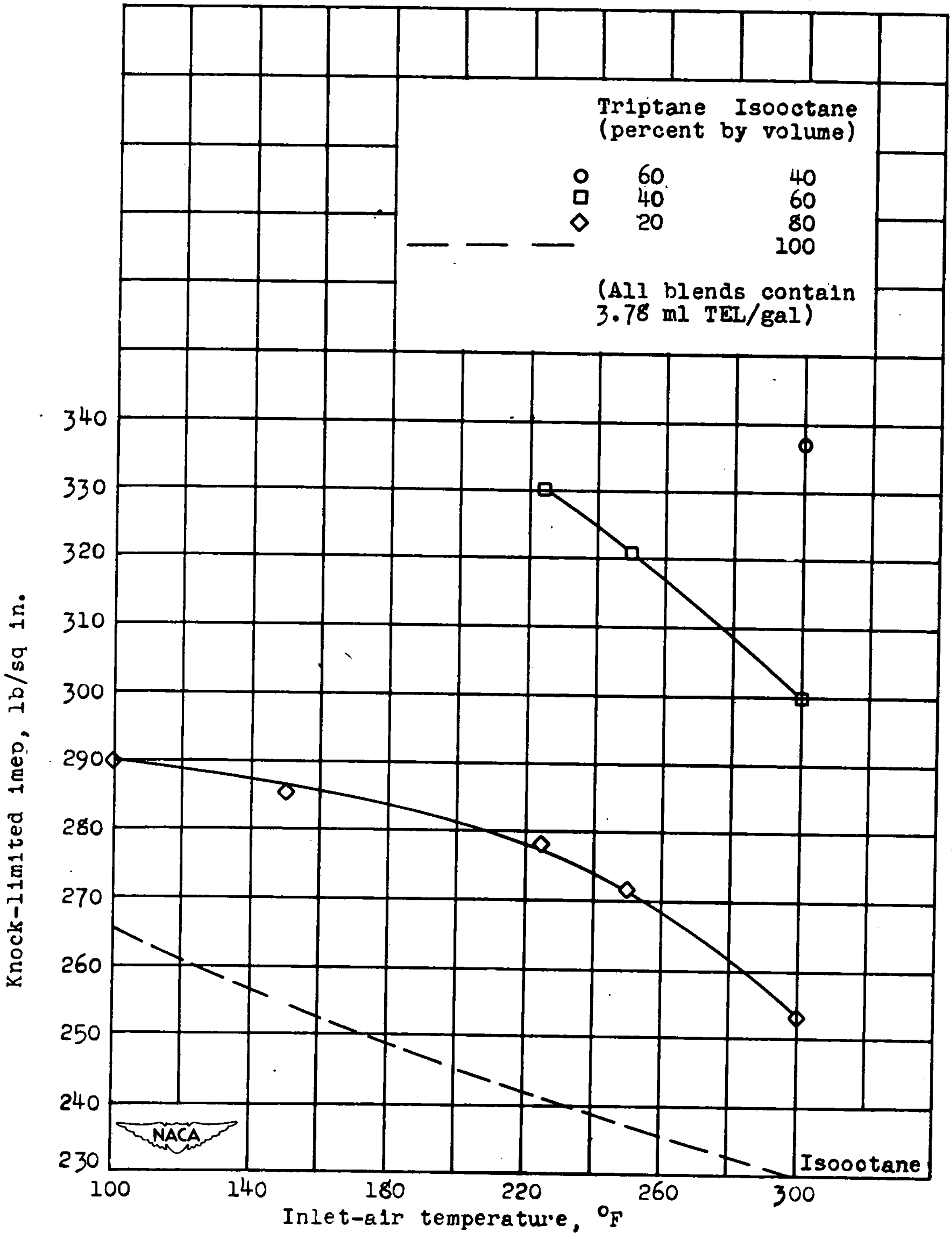
(b) Fuel-air ratio, 0.11.

Figure 8. - Concluded. Knock-limited performance of leaded blends of triptane and n-heptane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



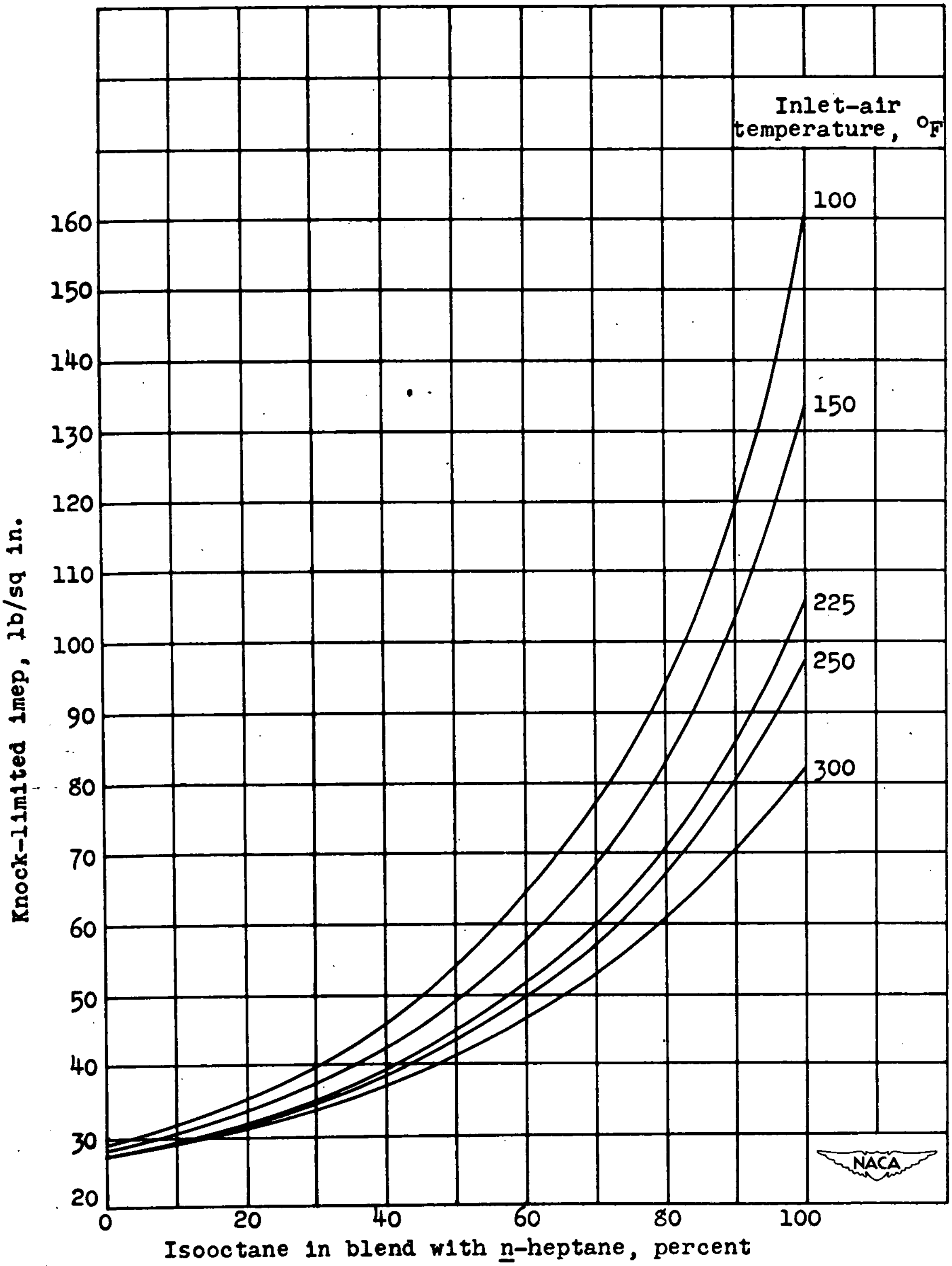
(a) Fuel-air ratio, 0.065.

Figure 9. - Knock-limited performance of leaded blends of triptane and isooctane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



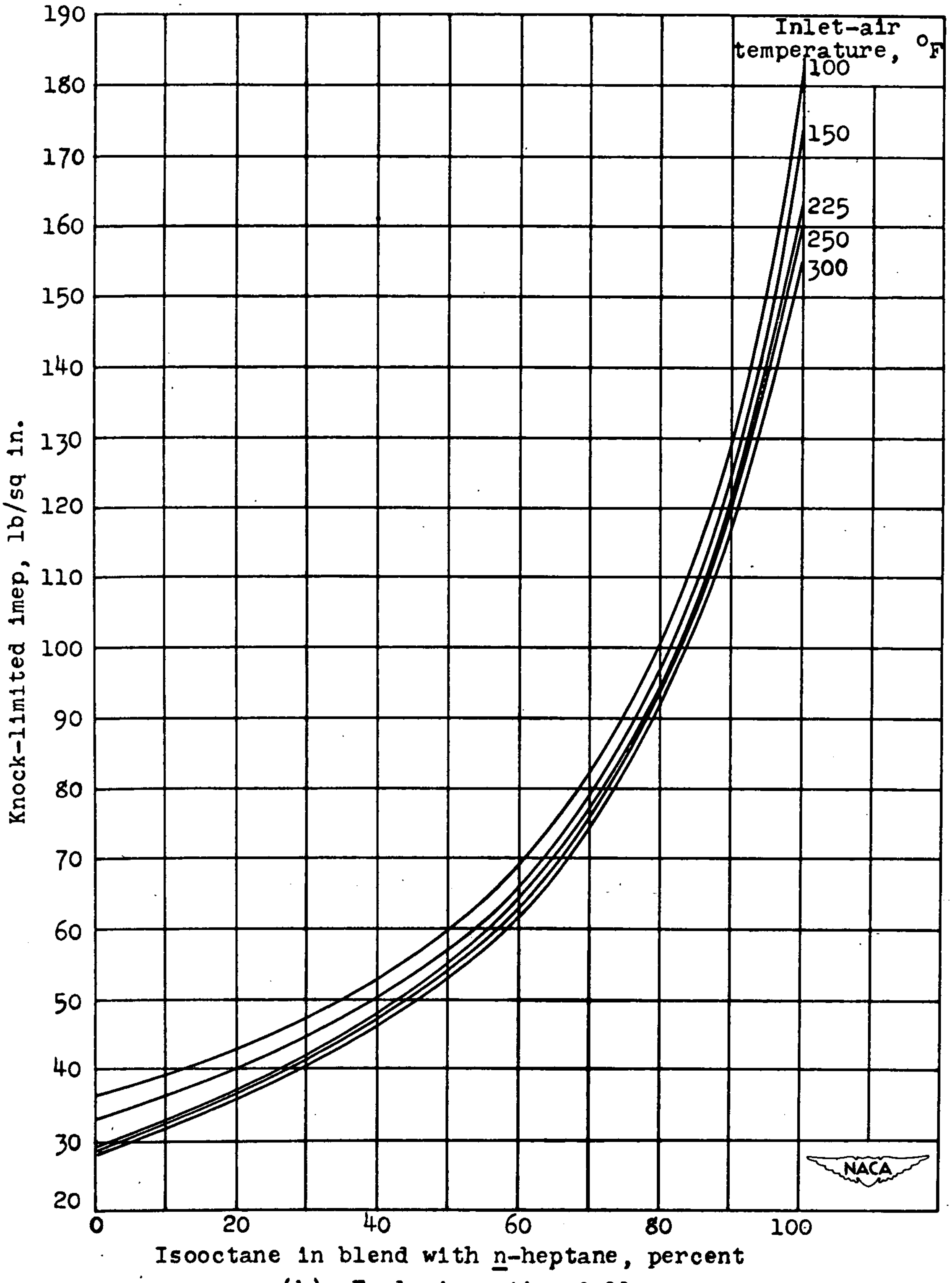
(b) Fuel-air ratio, 0.11.

Figure 9. - Concluded. Knock-limited performance of leaded blends of triptane and isooctane at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



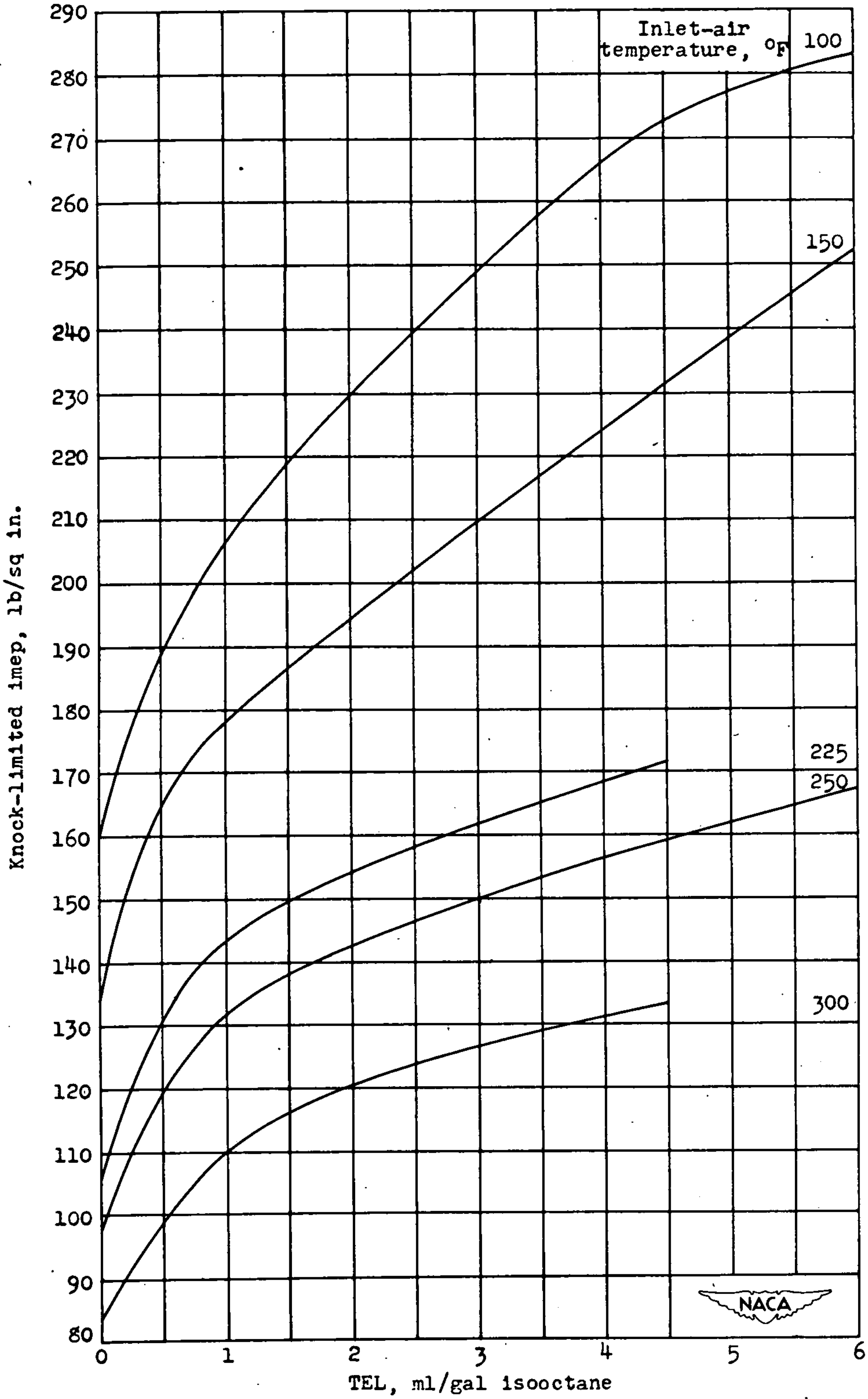
(a) Fuel-air ratio, 0.065.

Figure 10. - Rating curves for octane number determined in F-4 engine.



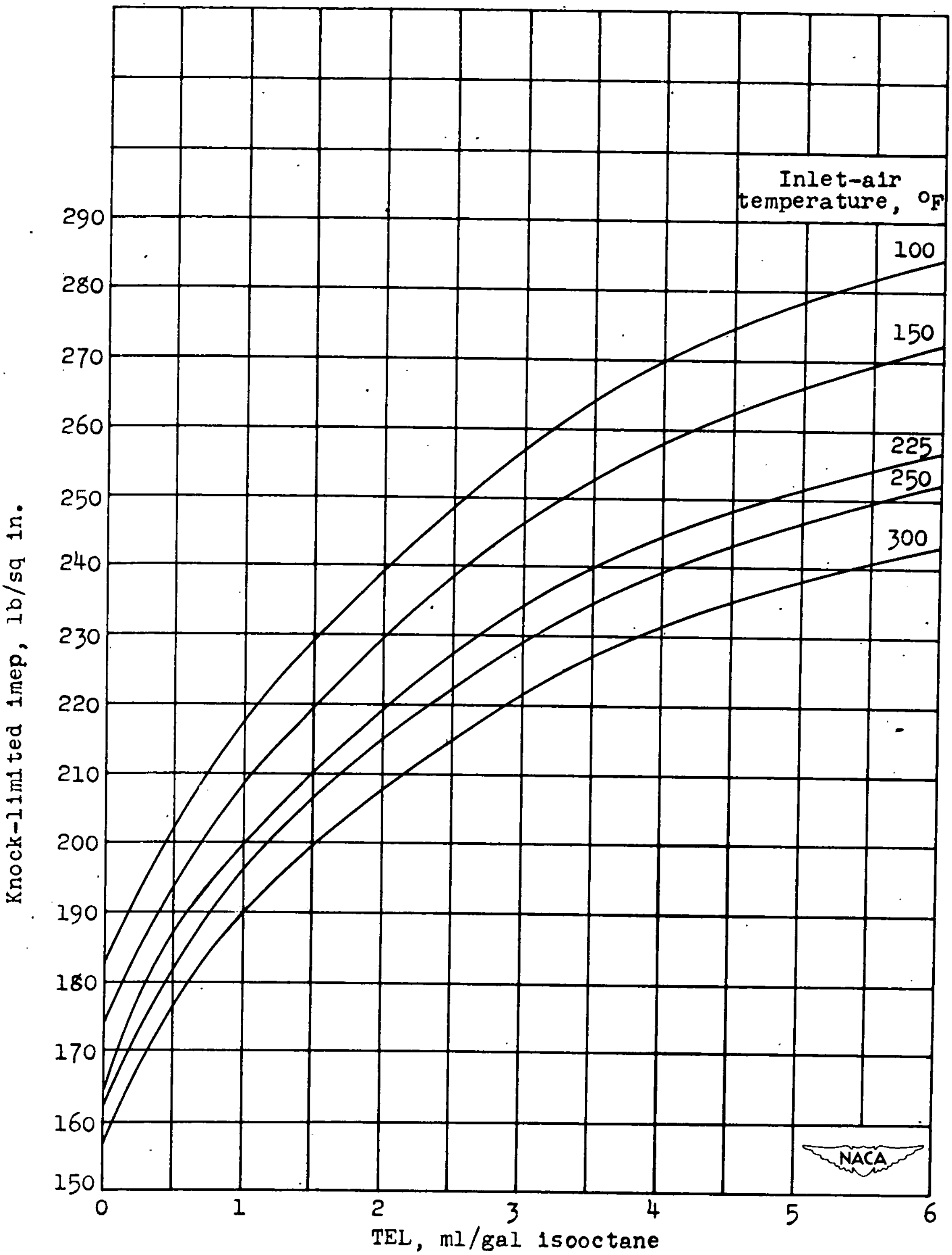
(b) Fuel-air ratio, 0.11.

Figure 10. - Concluded. Rating curves for octane number determined in F-4 engine.



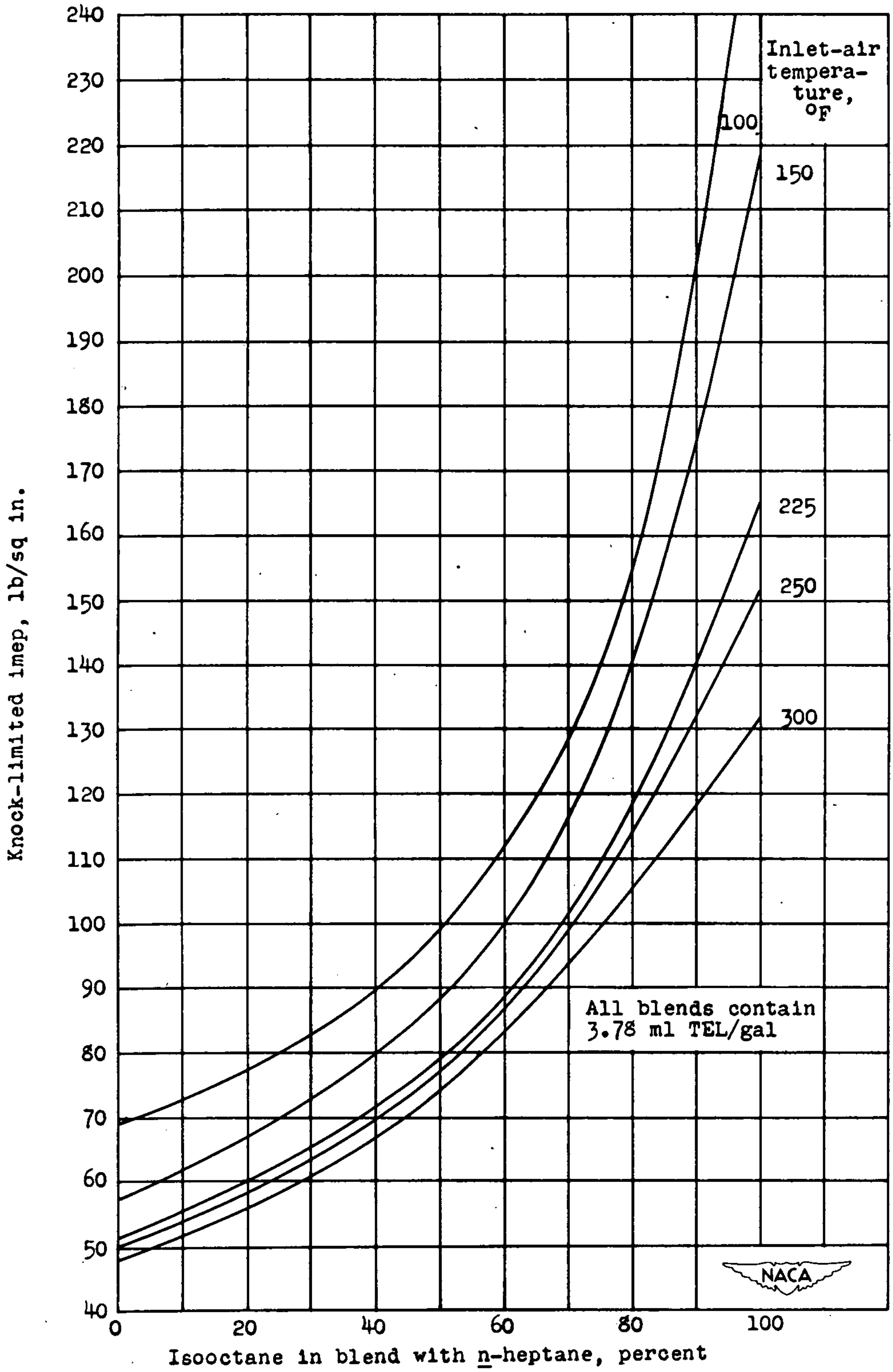
(a) Fuel-air ratio, 0.065.

Figure 11. - Rating curves in terms of leaded isooctane determined in F-4 engine.



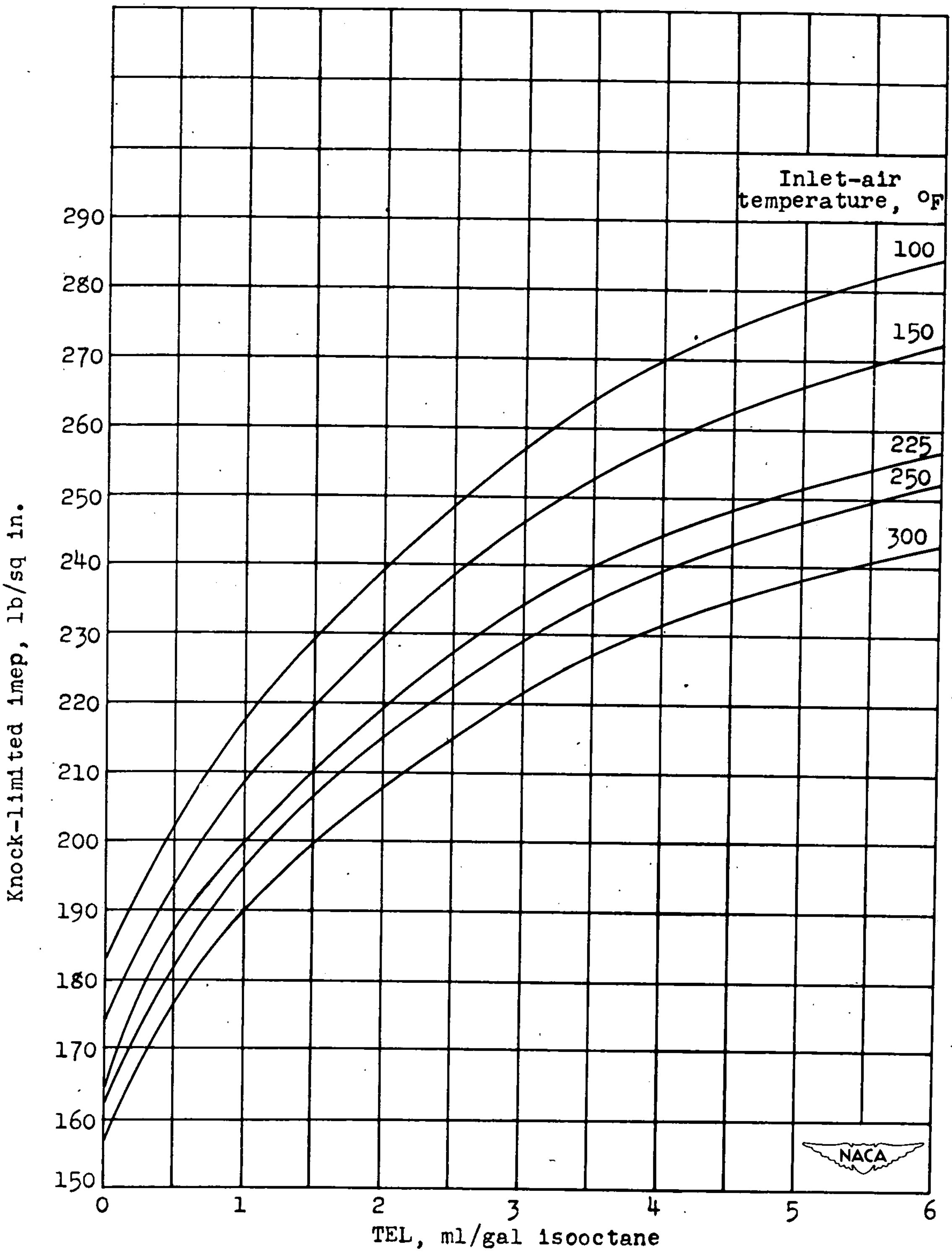
(b) Fuel-air ratio, 0.11.

Figure 11. - Concluded. Rating curves in terms of leaded isooctane determined in F-4 engine.



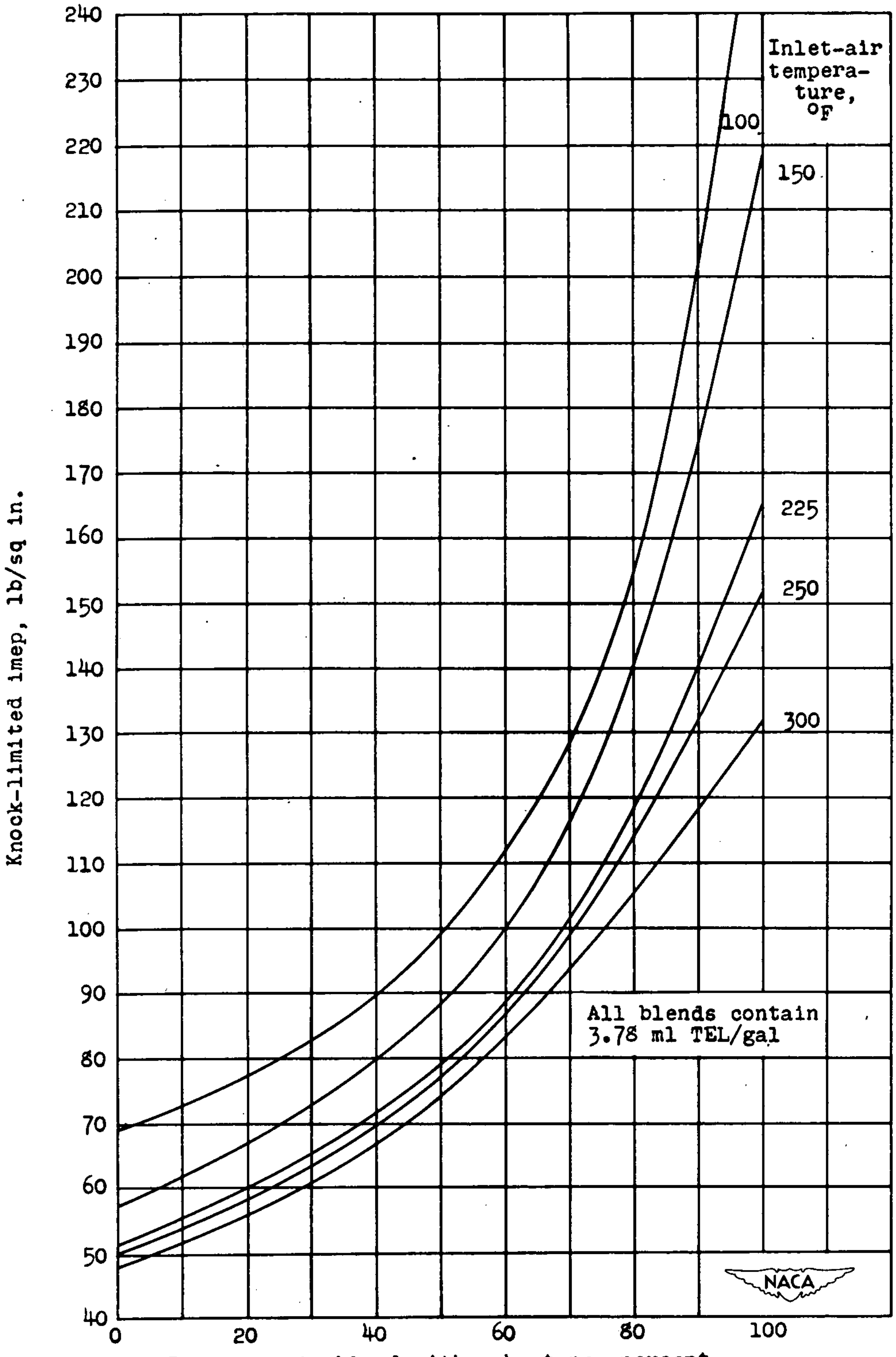
(a) Fuel-air ratio, 0.065.

Figure 12. - Rating curves in terms of leaded isooctane blended with leaded n-heptane determined in F-4 engine.



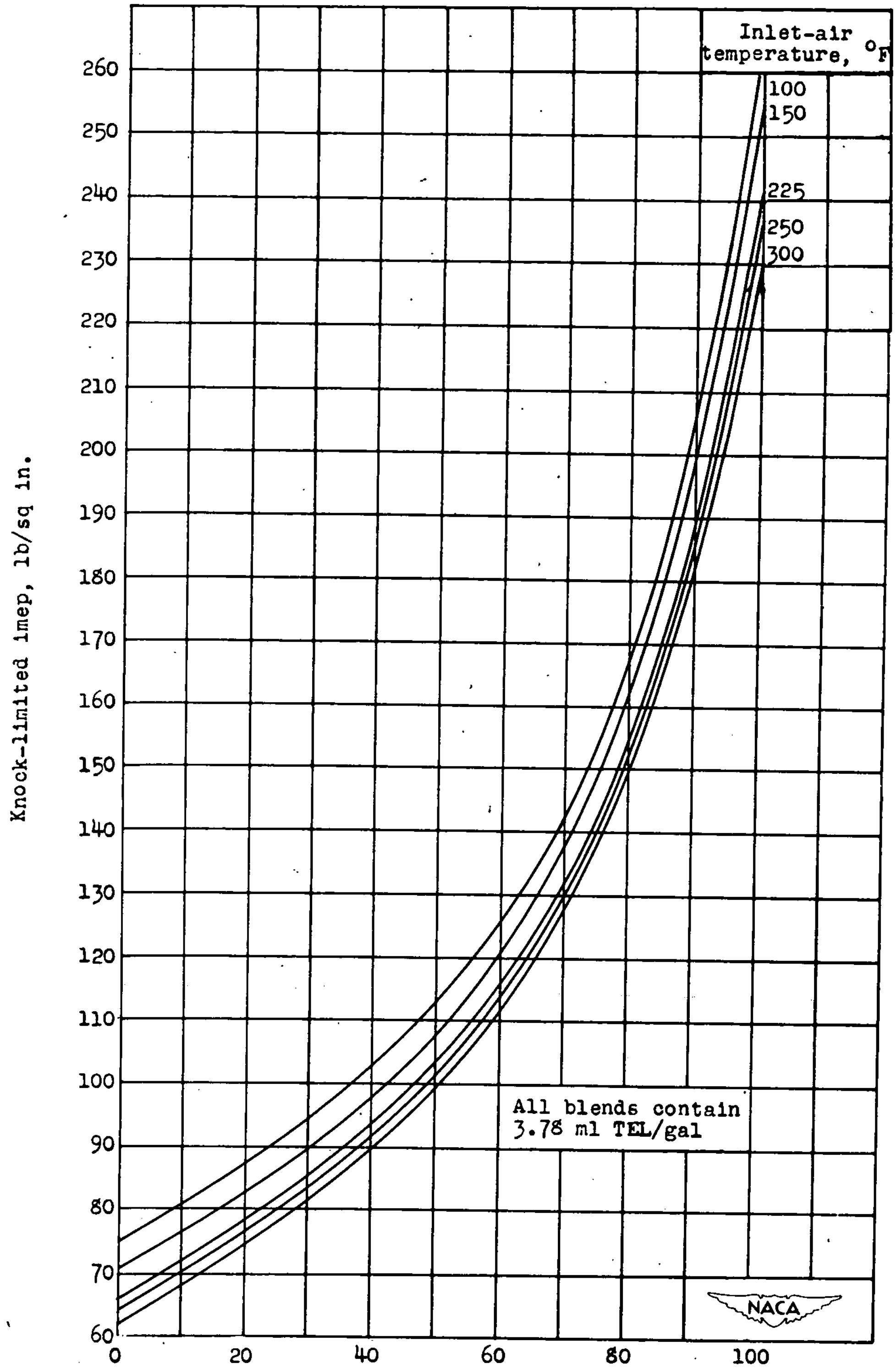
(b) Fuel-air ratio, 0.11.

Figure 11. - Concluded. Rating curves in terms of leaded isooctane determined in F-4 engine.



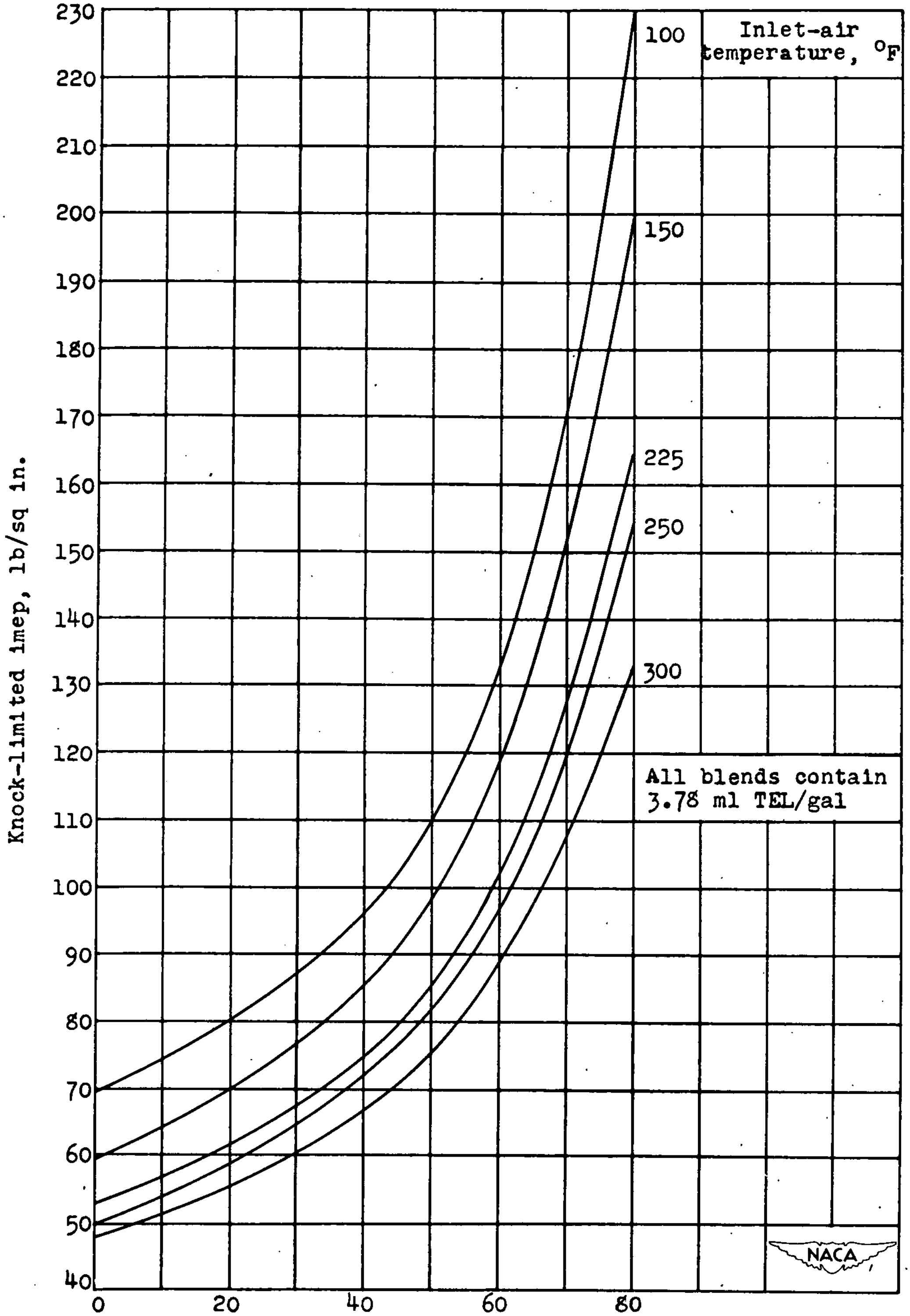
(a) Fuel-air ratio, 0.065.

Figure 12. - Rating curves in terms of leaded isooctane blended with leaded n-heptane determined in F-4 engine.



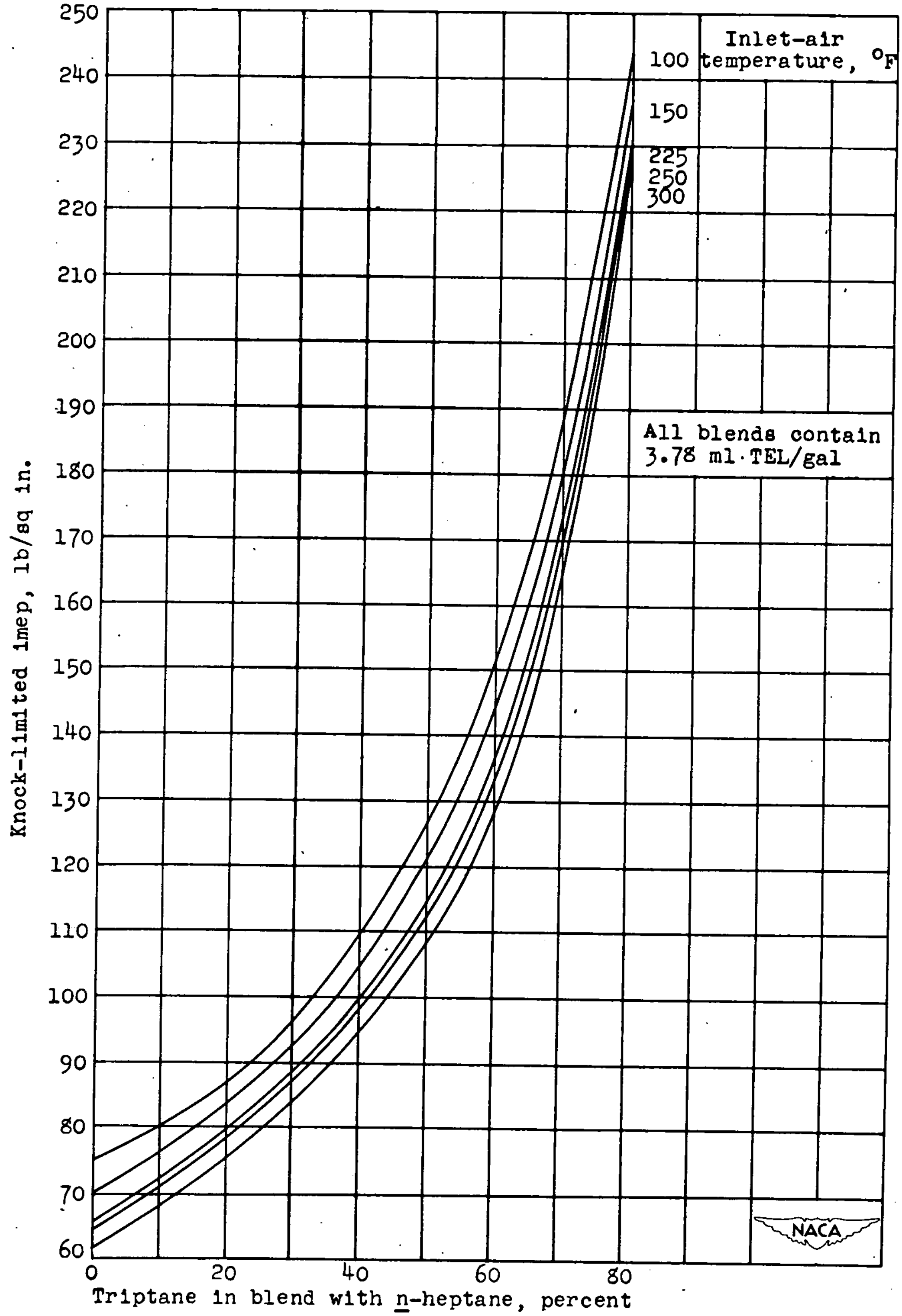
(b) Fuel-air ratio, 0.11.

Figure 12. - Concluded. Rating curves in terms of leaded isooctane blended with leaded n-heptane determined in F-4 engine.



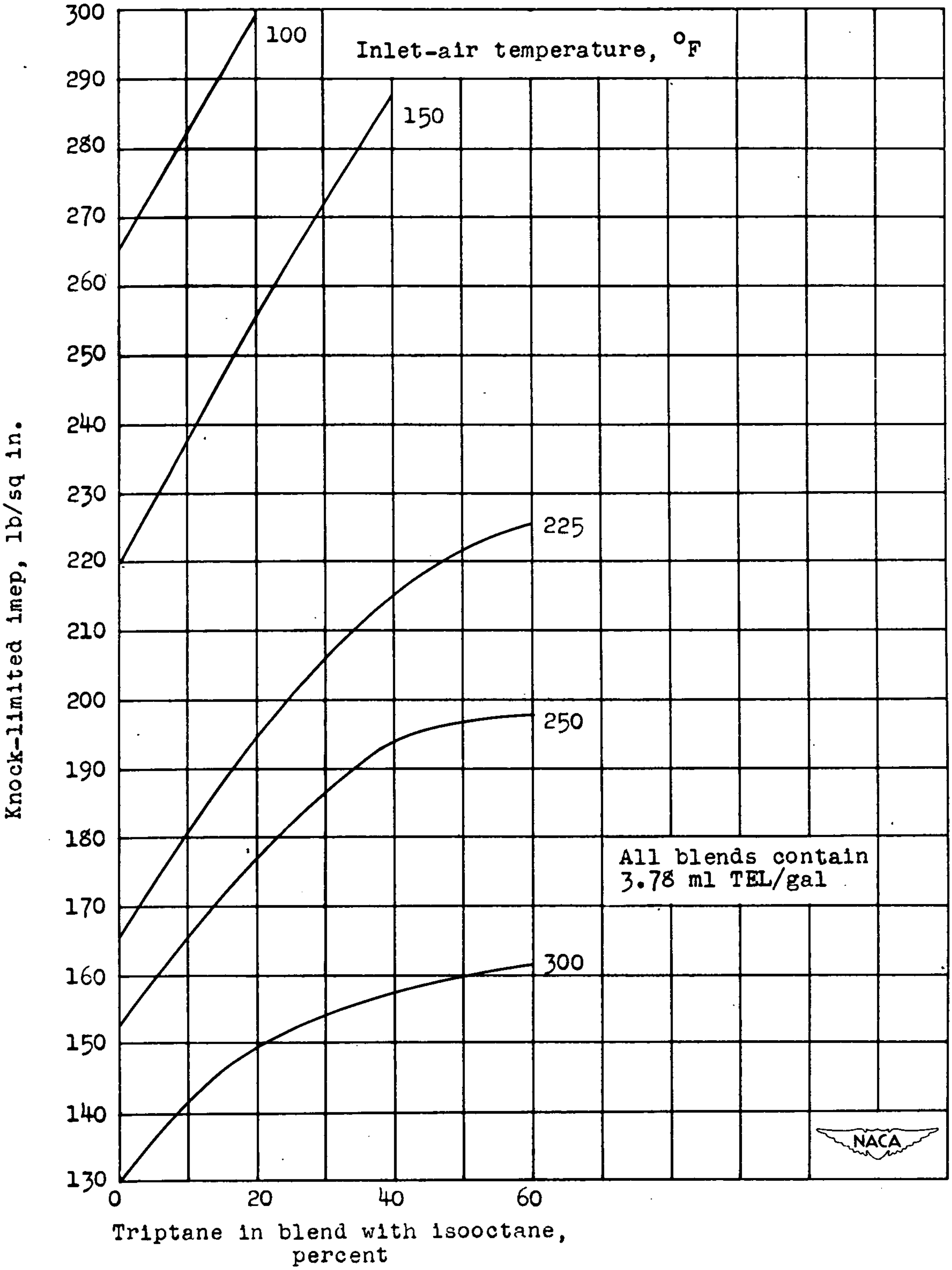
(a) Fuel-air ratio, 0.065.

Figure 13. - Rating curves in terms of leaded triptane blended with leaded n-heptane determined in F-4 engine.



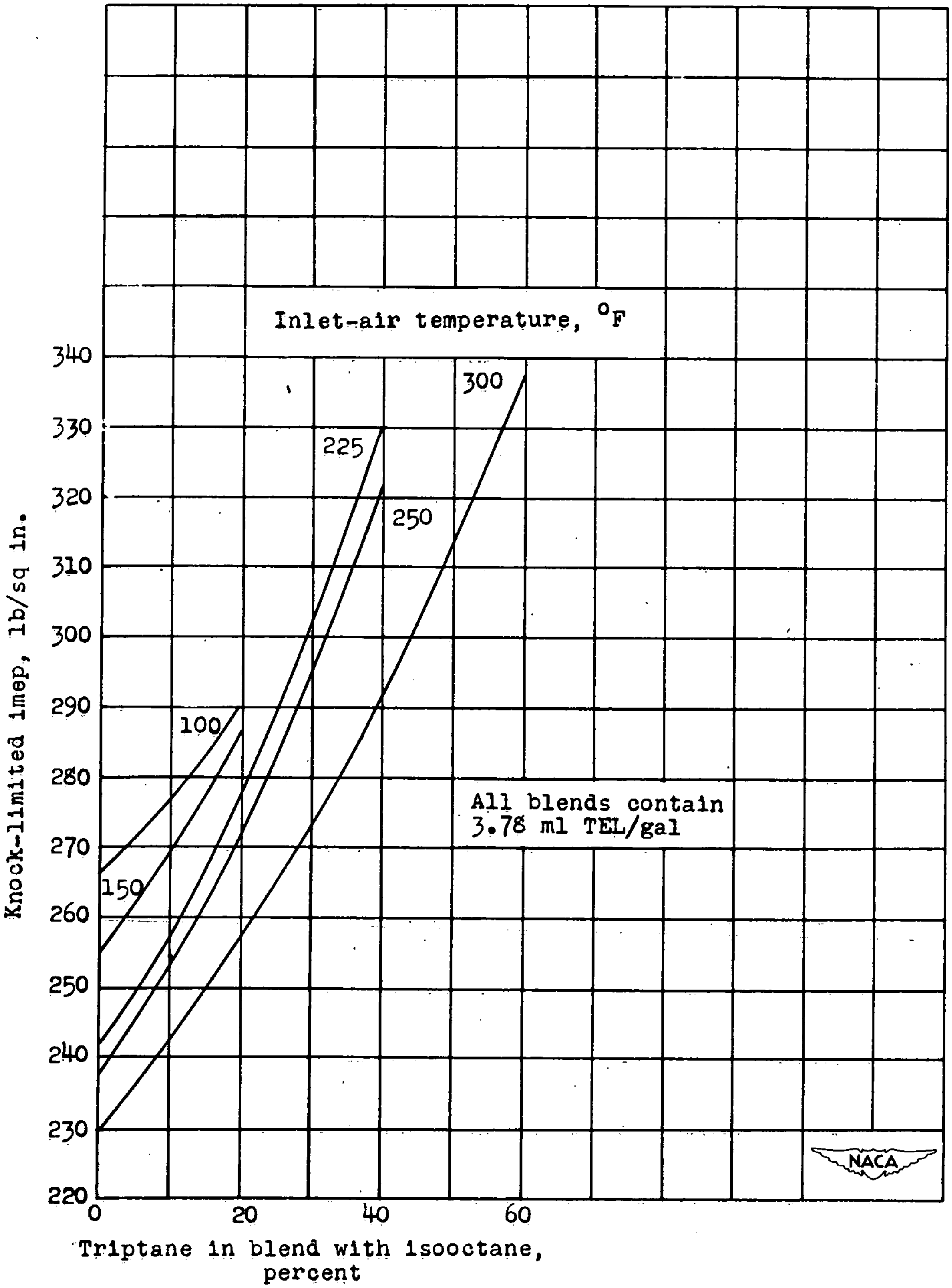
(b) Fuel-air ratio, 0.11.

Figure 13. - Concluded. Rating curves in terms of leaded triptane blended with leaded n-heptane determined in F-4 engine.



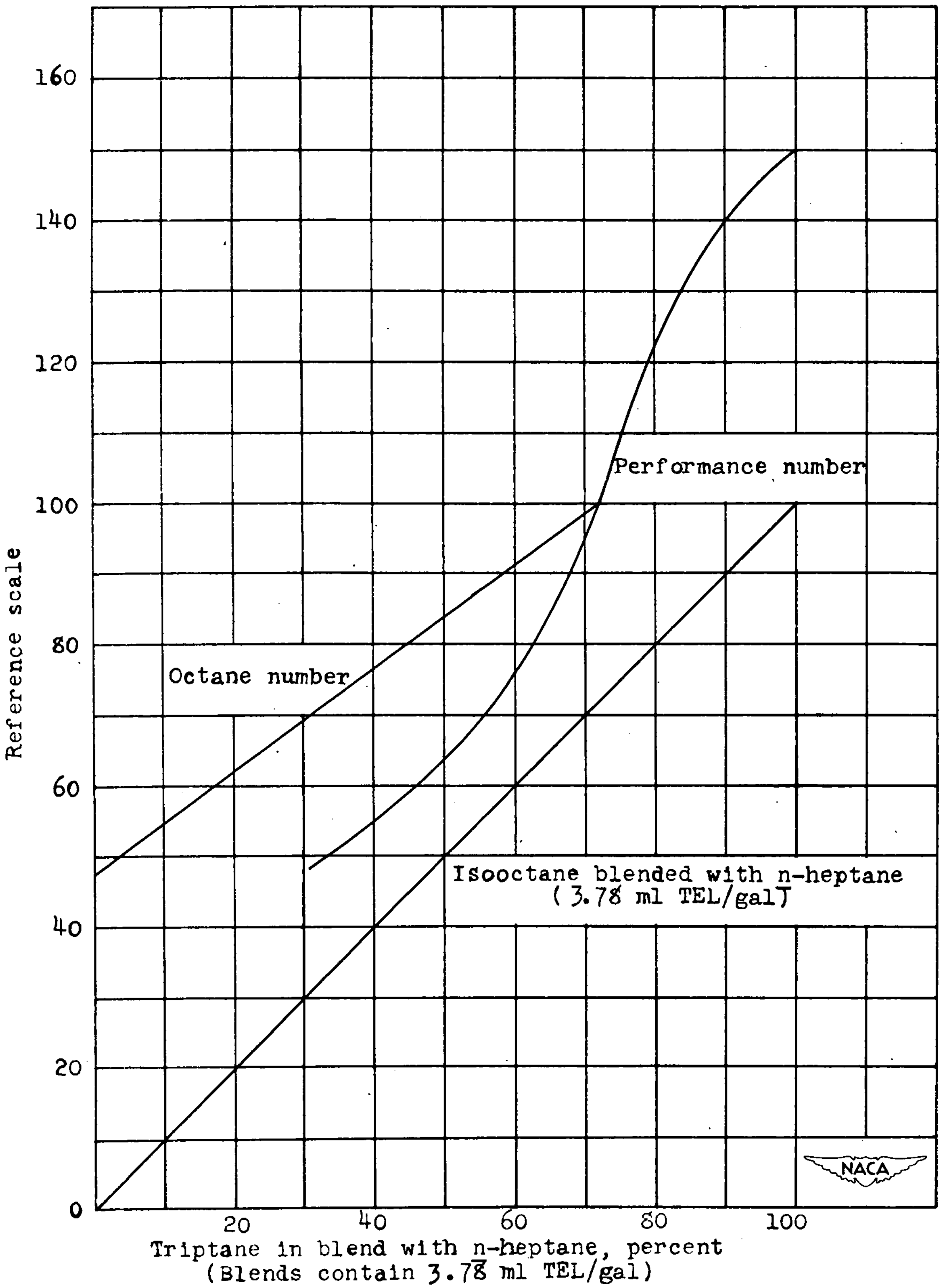
(a) Fuel-air ratio, 0.065.

Figure 14. - Rating curves in terms of leaded triptane blended with leaded isooctane determined in F-4 engine.



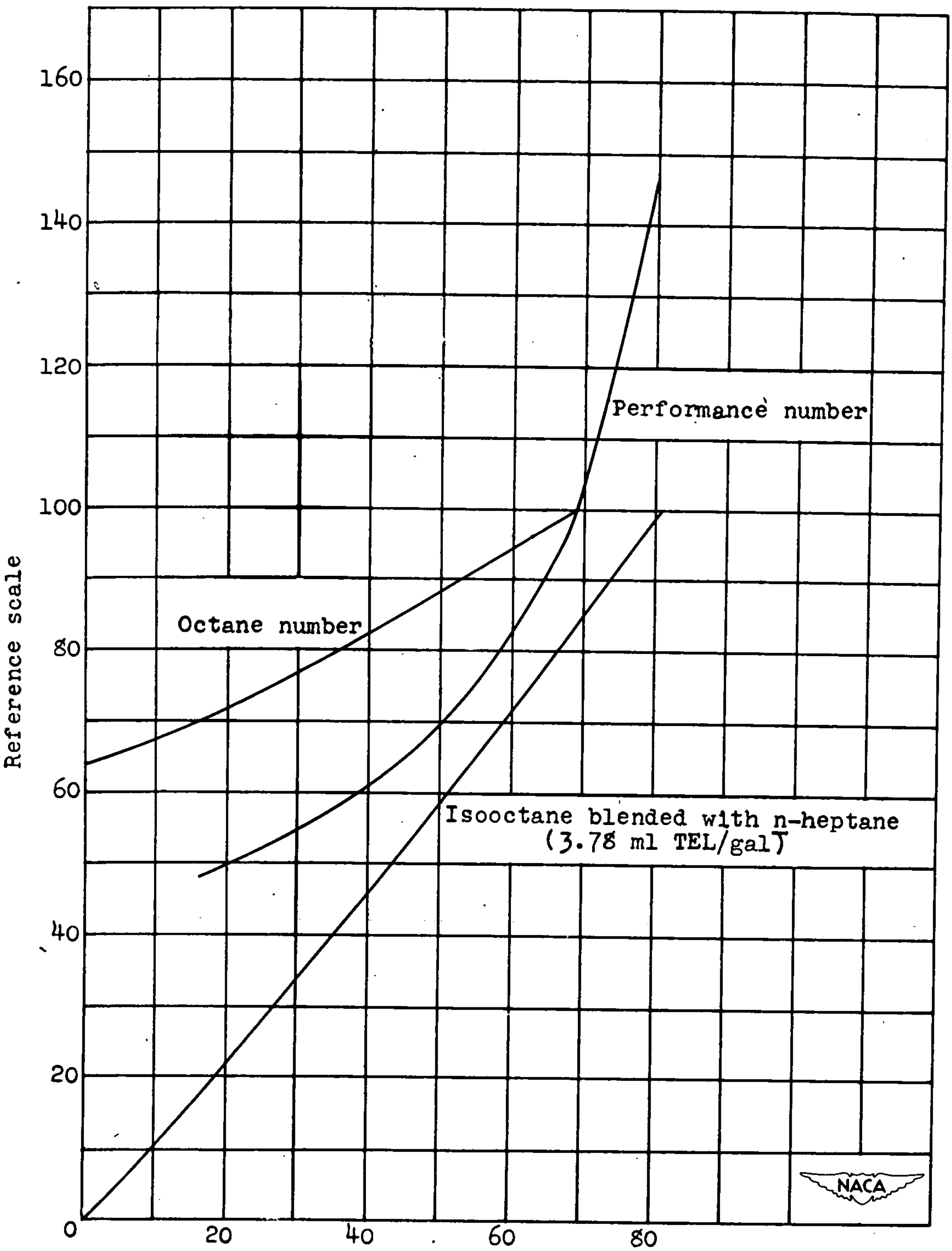
(b) Fuel-air ratio, 0.11.

Figure 14. - Concluded. Rating curves in terms of leaded triptane blended with leaded isooctane determined in F-4 engine.



(a) F-3 engine at standard conditions.

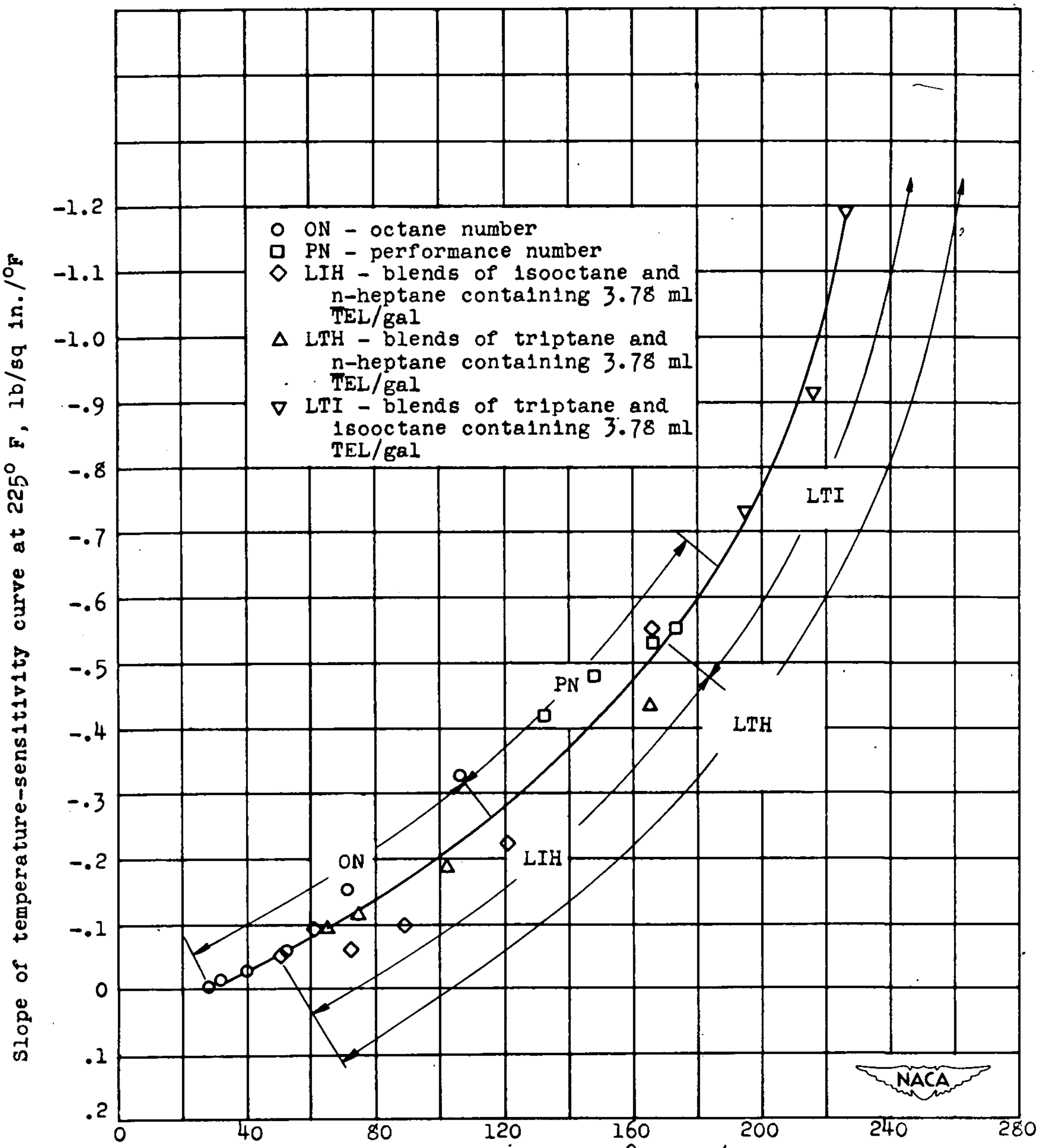
Figure 15. - Relations among various rating scales.



Triptane in blend with n-heptane, percent
(Blends contain 3.78 ml TEL/gal)

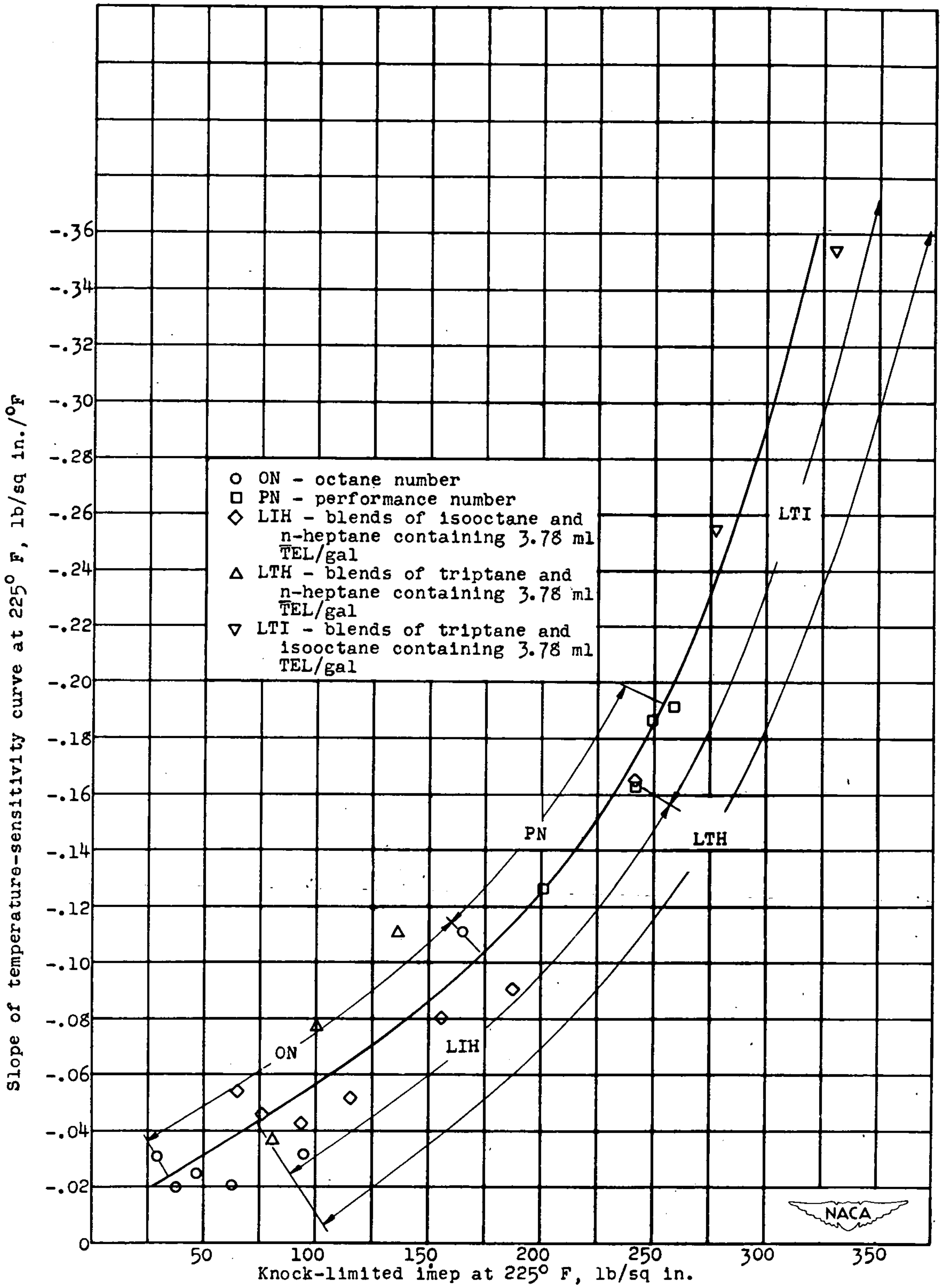
(b) F-4 engine at standard conditions;
fuel-air ratio, 0.11.

Figure 15. - Concluded. Relations among various rating scales.



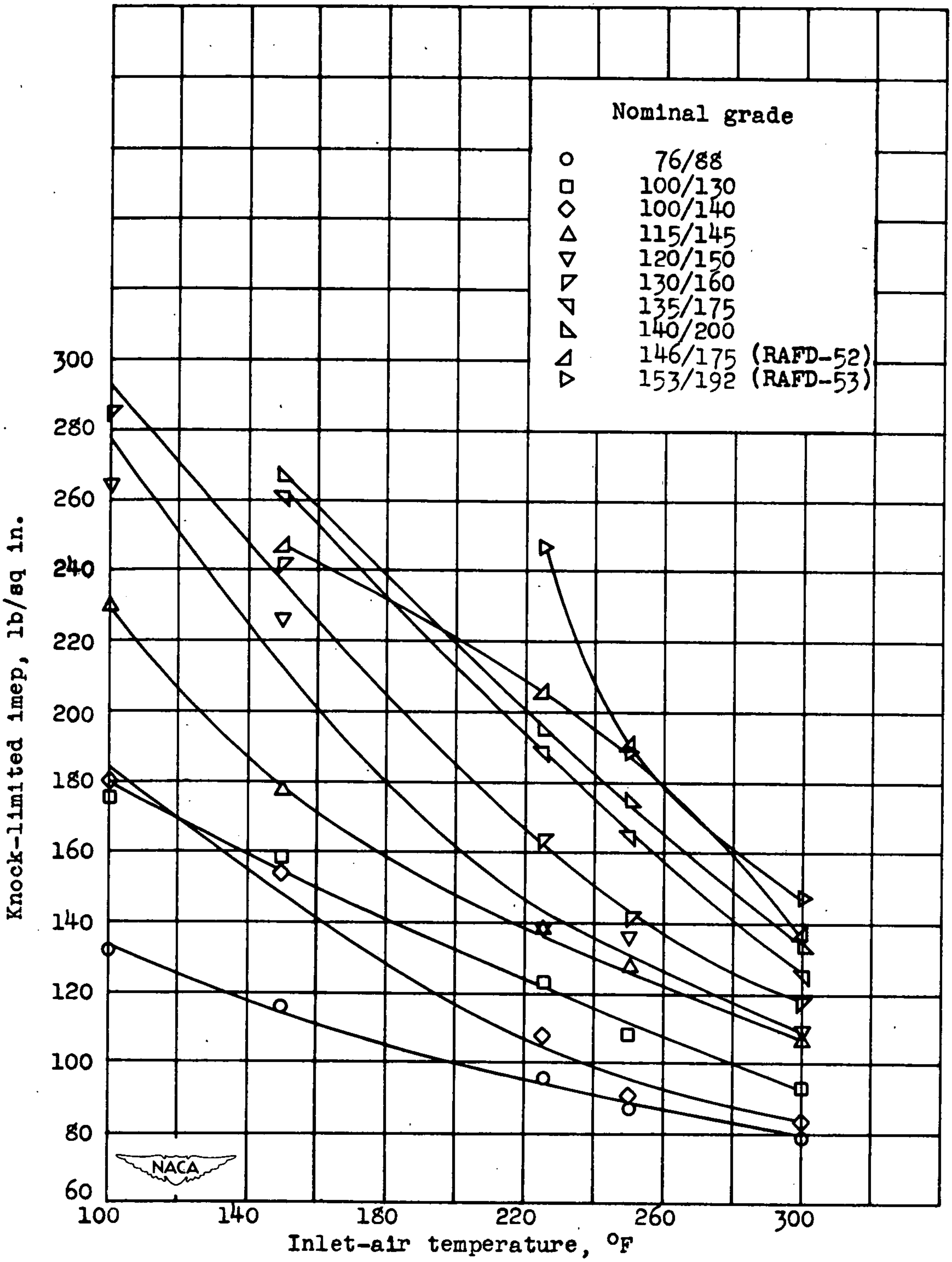
(a) Fuel-air ratio, 0.065.

Figure 16. - Variation of temperature sensitivity with knock-limited performance in F-4 engine for various reference fuel blends.



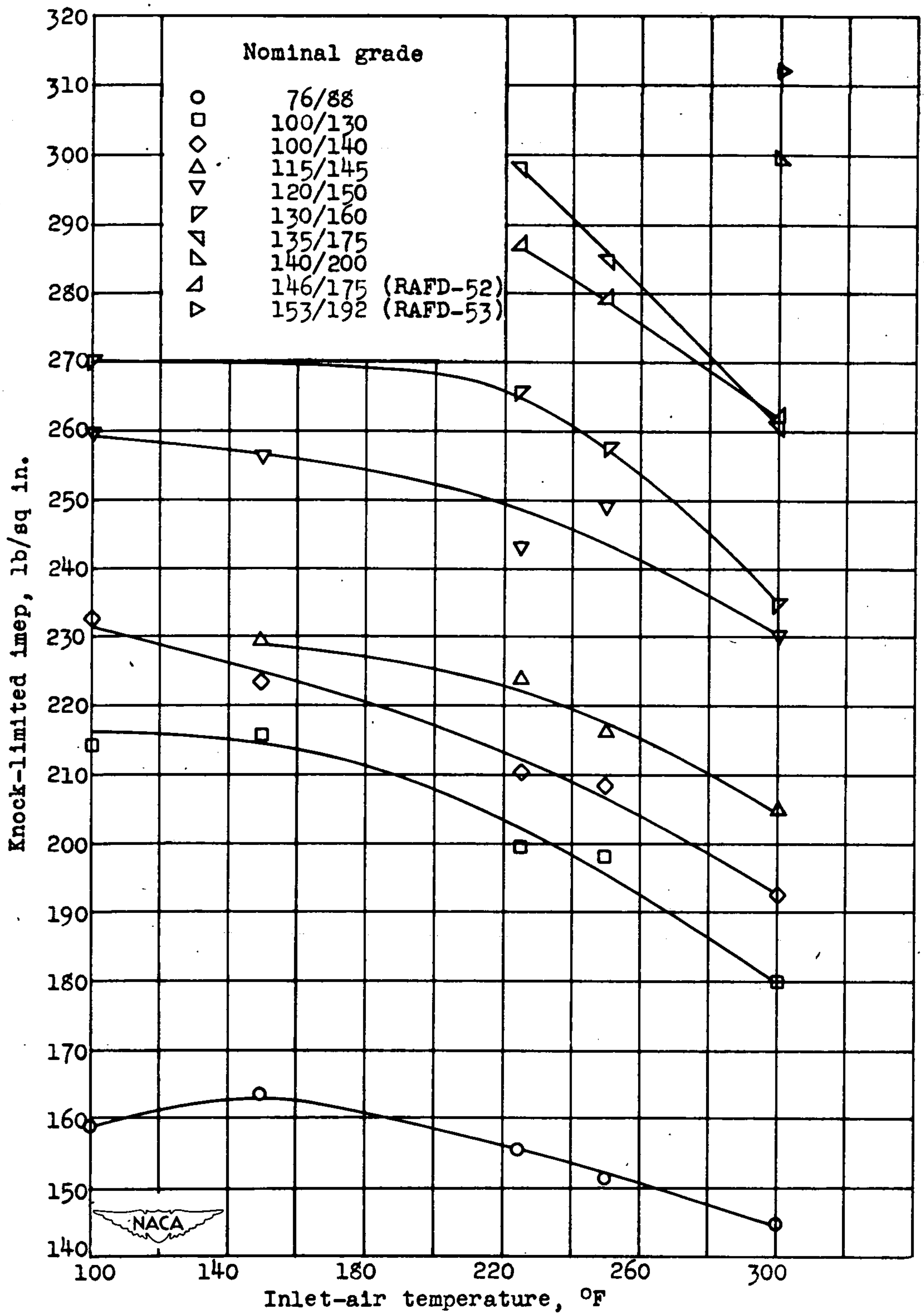
(b) Fuel-air ratio, 0.11.

Figure 16. - Concluded. Variation of temperature sensitivity with knock-limited performance in F-4 engine for various reference fuel blends.



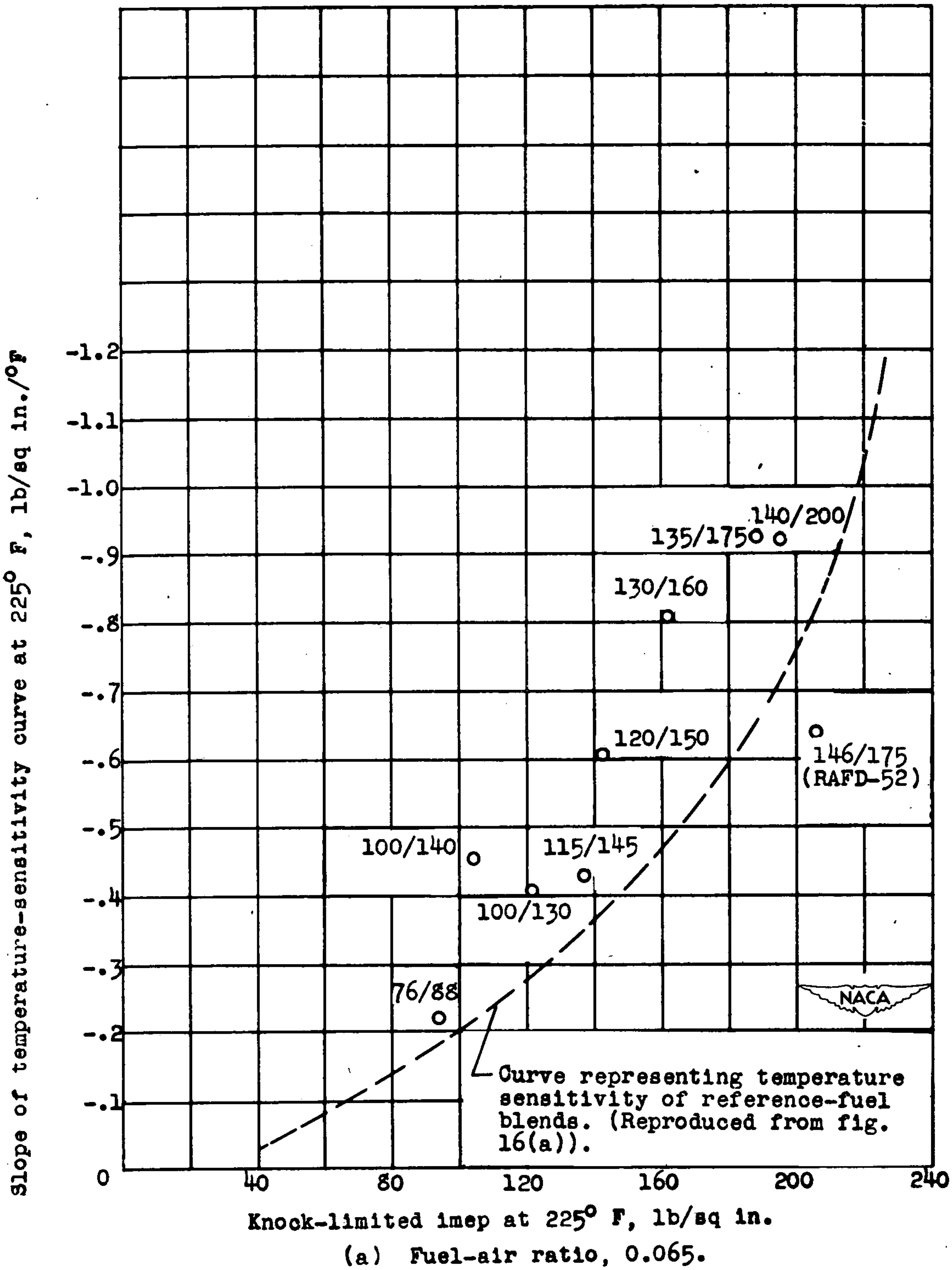
(a) Fuel-air ratio, 0.065.

Figure 17. - Knock-limited performance of service-type fuels at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



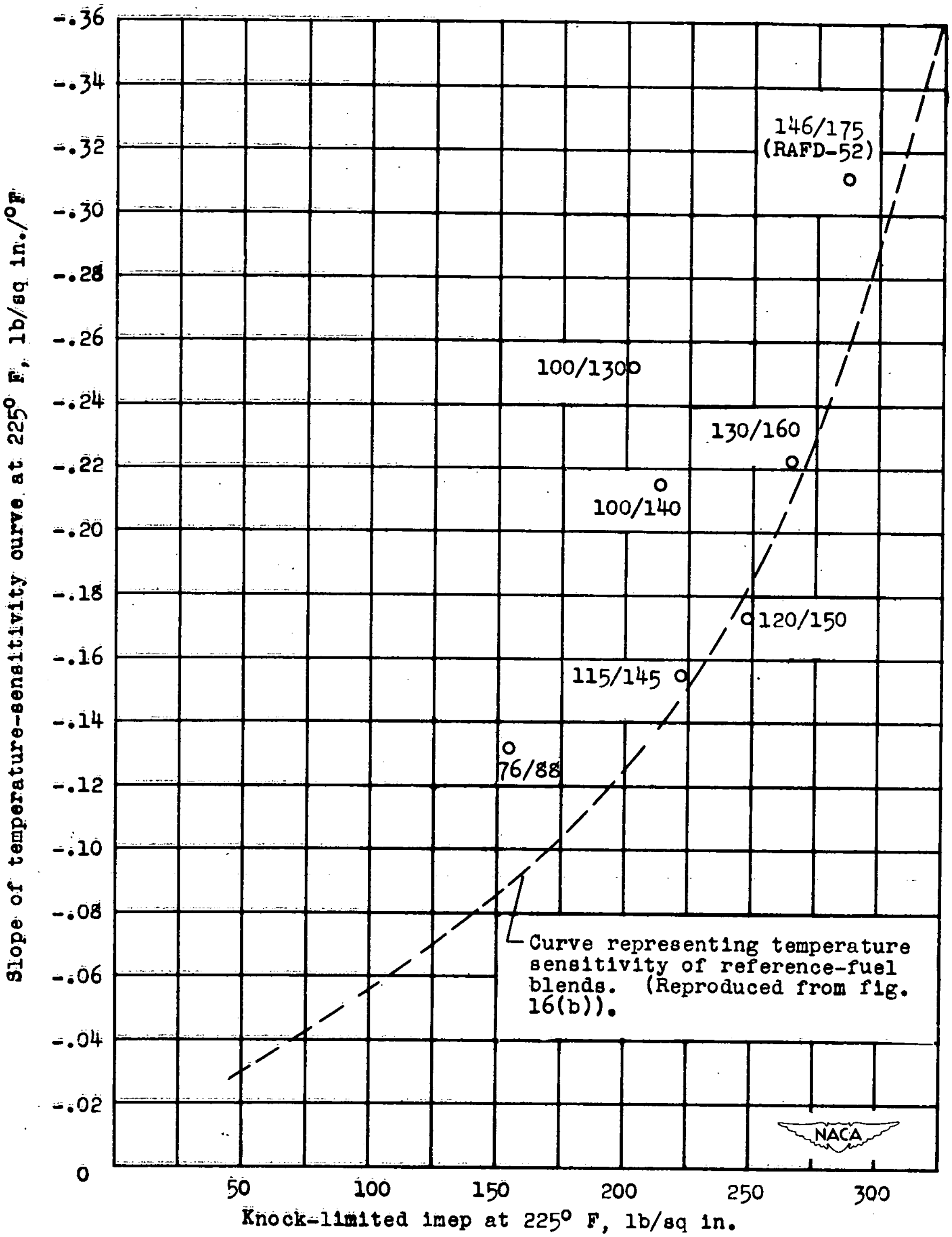
(b) Fuel-air ratio, 0.11.

Figure 17. - Concluded. Knock-limited performance of service-type fuels at various inlet-air temperatures in F-4 engine. All conditions other than inlet-air temperature were standard.



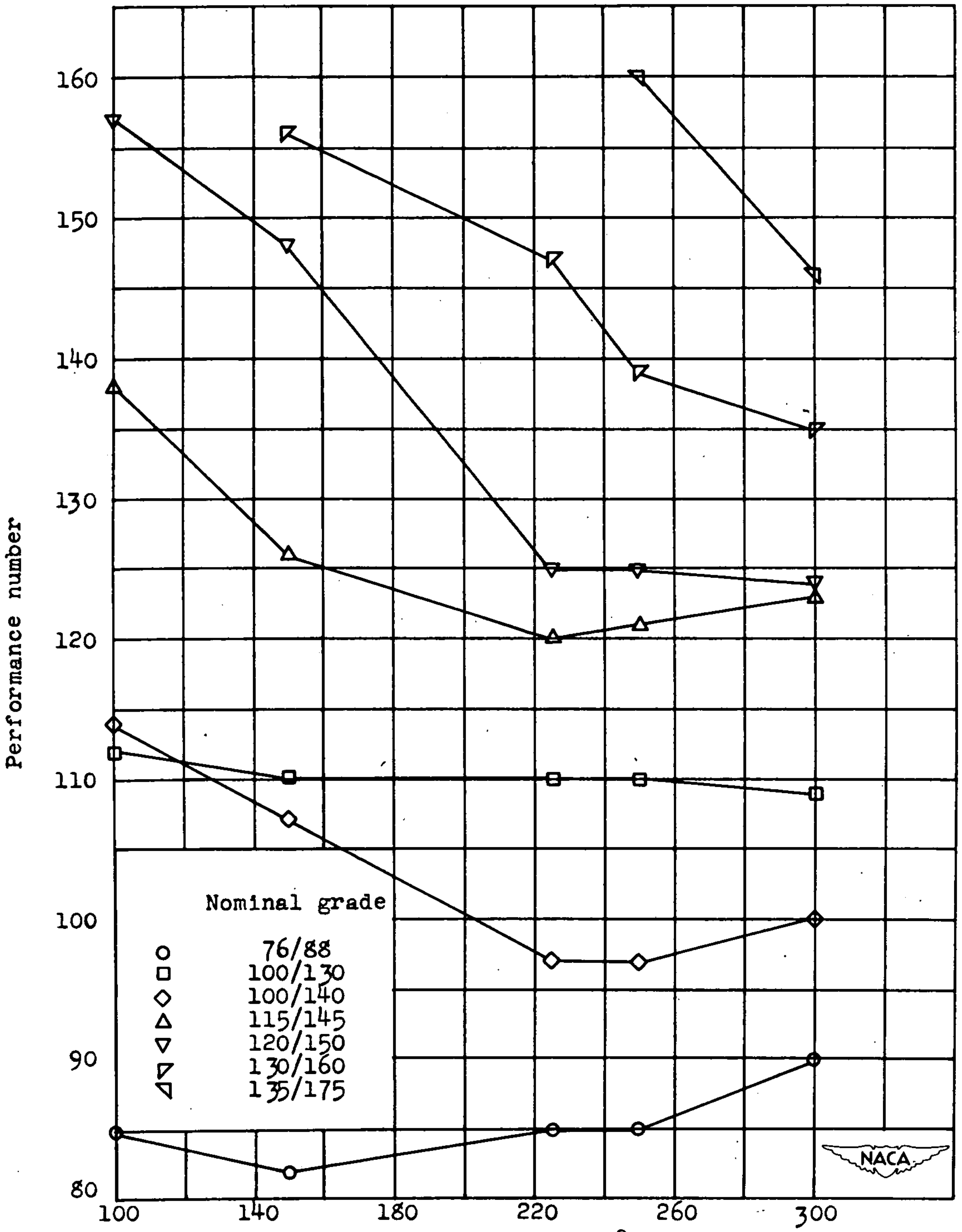
(a) Fuel-air ratio, 0.065.

Figure 18. - Comparison between temperature sensitivities of reference-fuel blends and service-type fuels in F-4 engine.



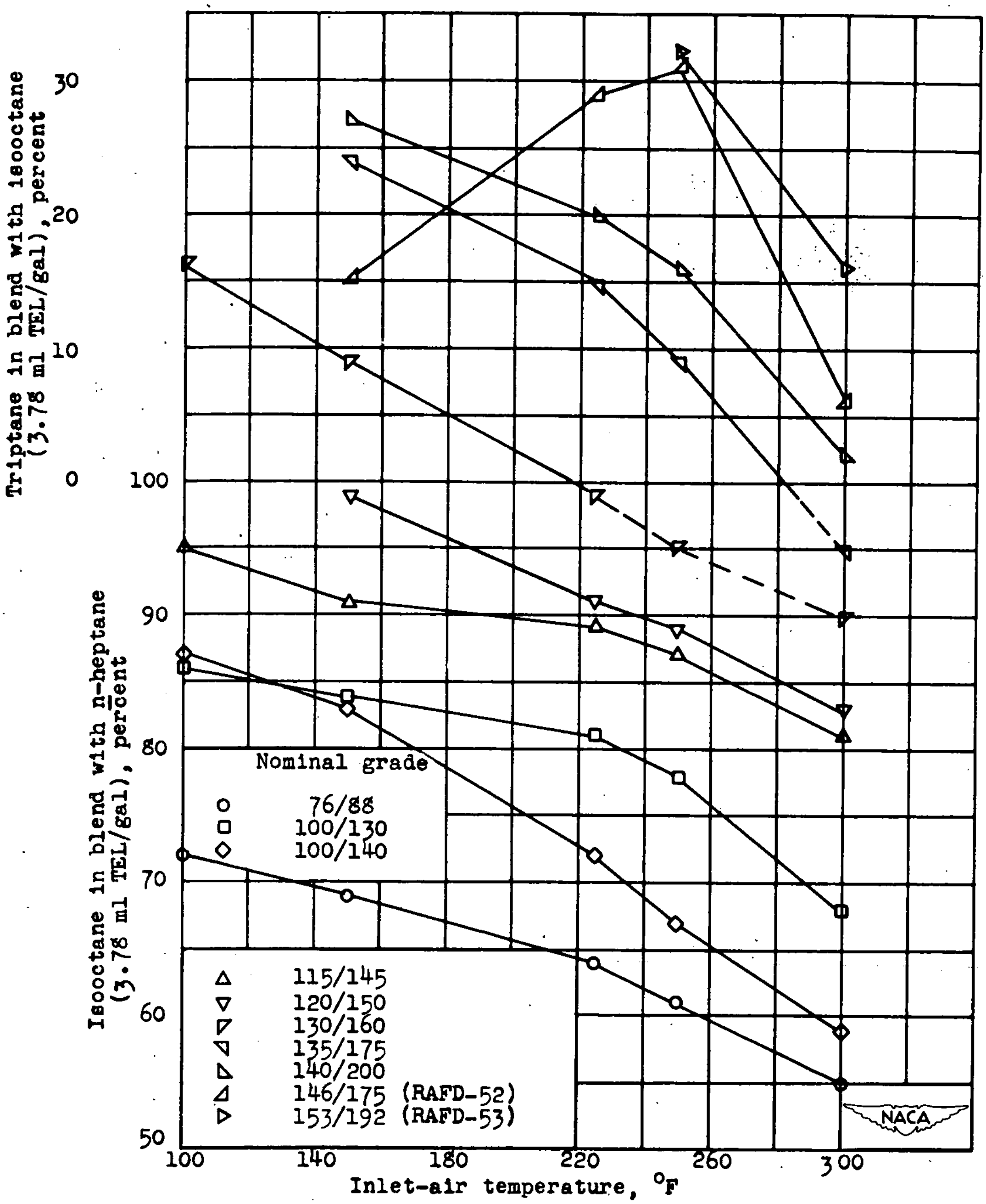
(b) Fuel-air ratio, 0.11.

Figure 18. - Concluded. Comparison between temperature sensitivities of reference-fuel blends and service-type fuels in F-4 engine.



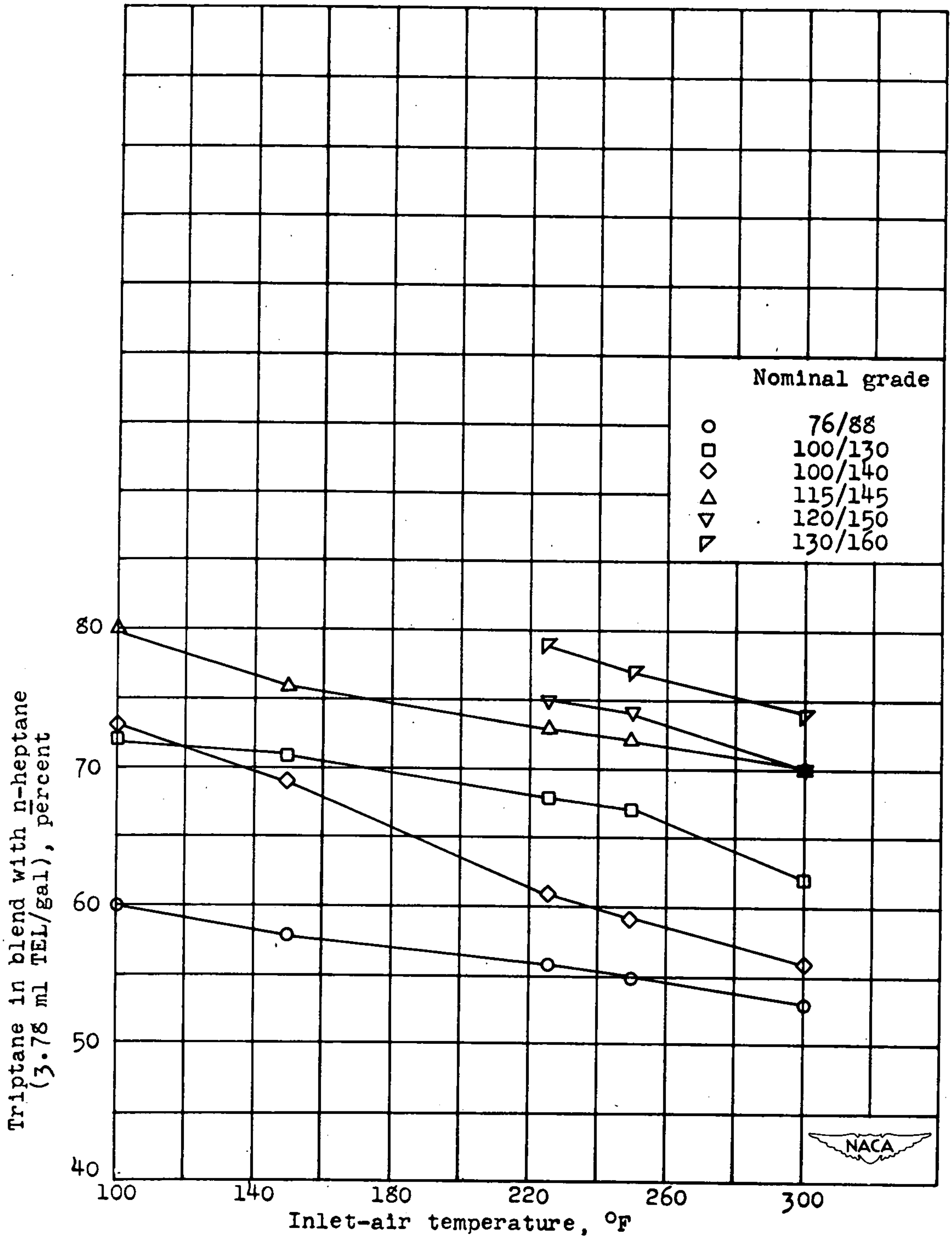
(a) Performance-number scale.

Figure 19. - Effect of inlet-air temperature on lean (fuel-air ratio, 0.065) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



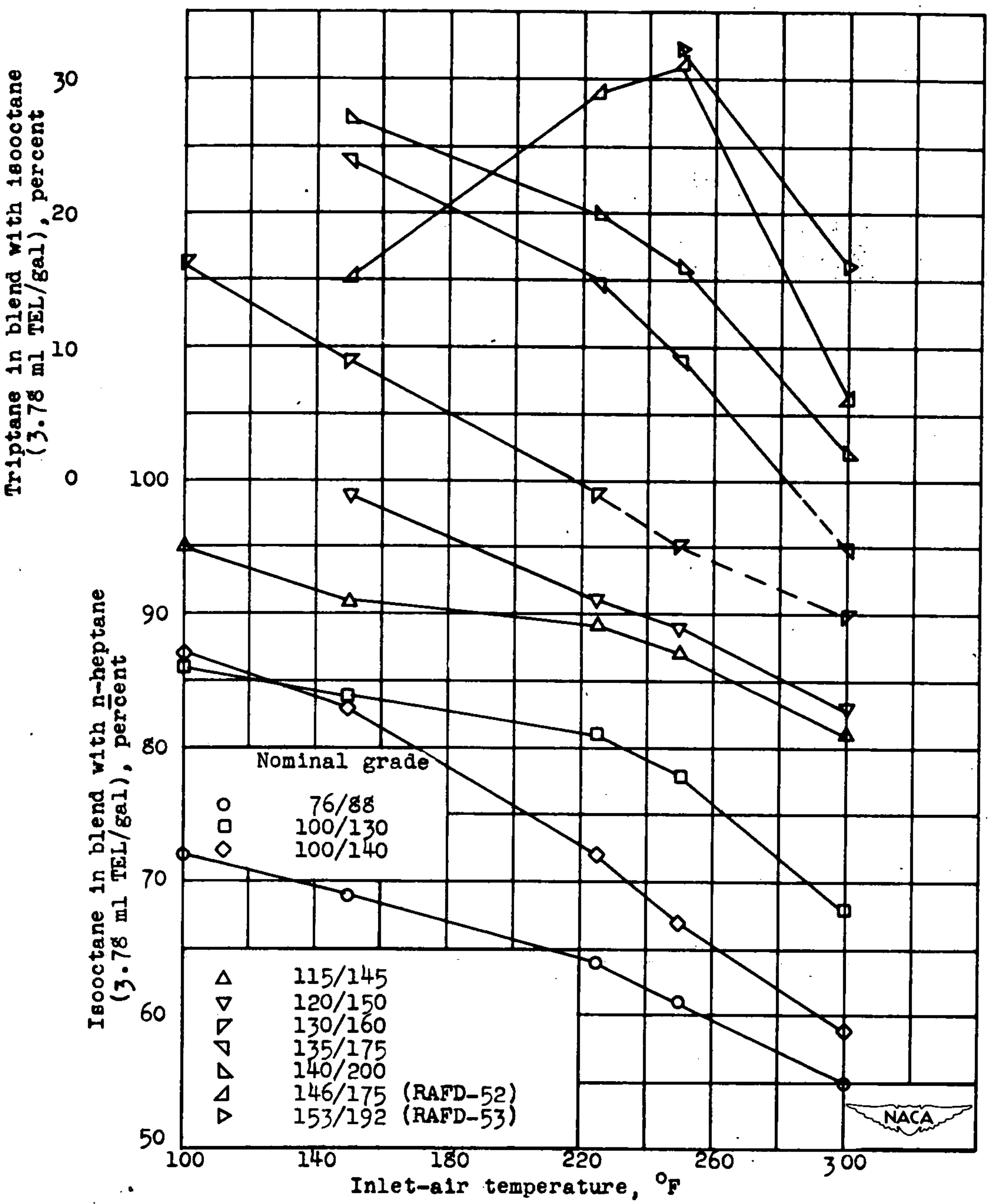
(b) Leaded isooctane - n-heptane and leaded triptane-isooctane scales.

Figure 19. - Continued. Effect of inlet-air temperature on lean (fuel-air ratio, 0.065) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



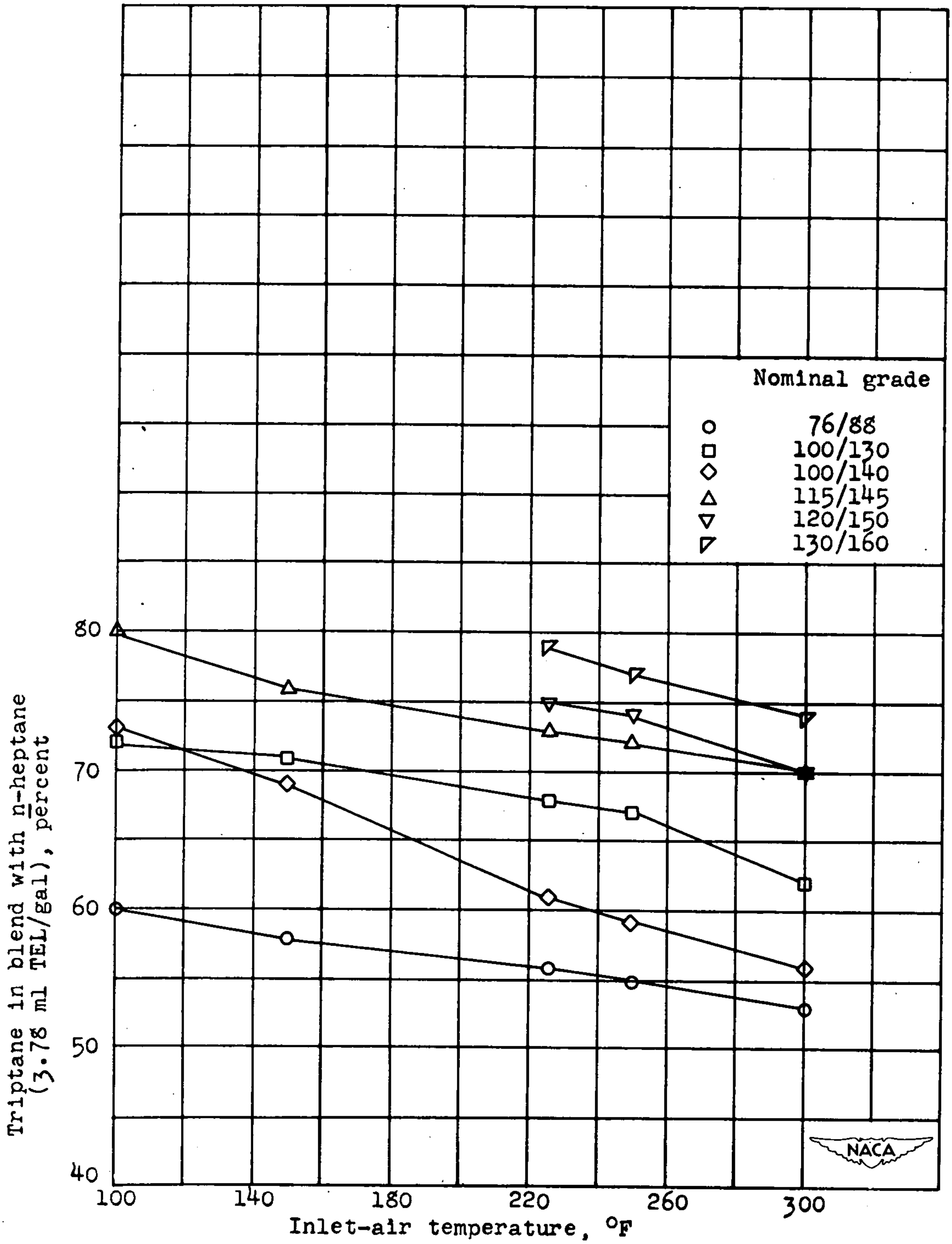
(c) Leaded triptane - n-heptane scale.

Figure 19. - Concluded. Effect of inlet-air temperature on lean (fuel-air ratio, 0.065) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



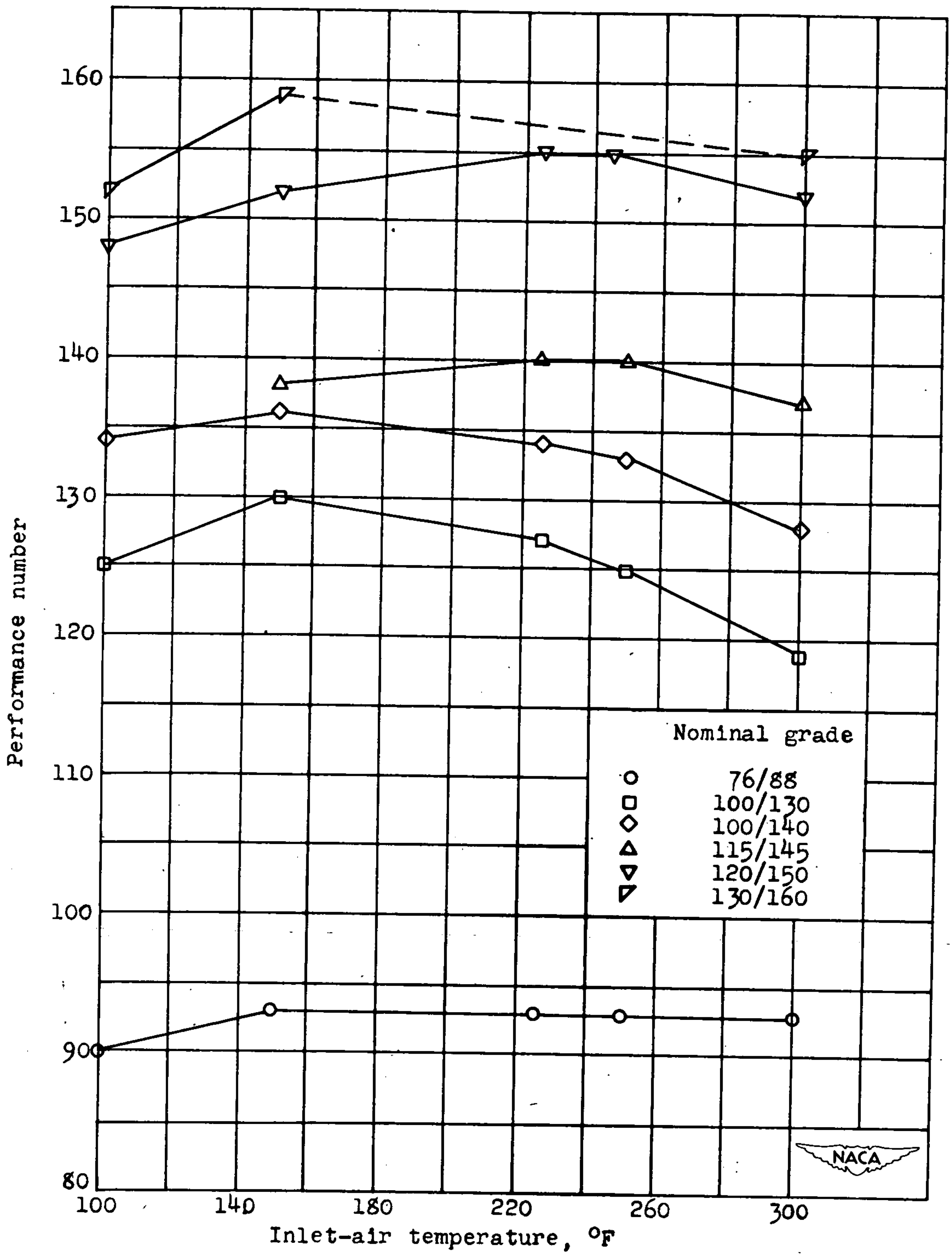
(b) Leaded isooctane - n-heptane and leaded triptane-isooctane scales.

Figure 19. - Continued. Effect of inlet-air temperature on lean (fuel-air ratio, 0.065) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



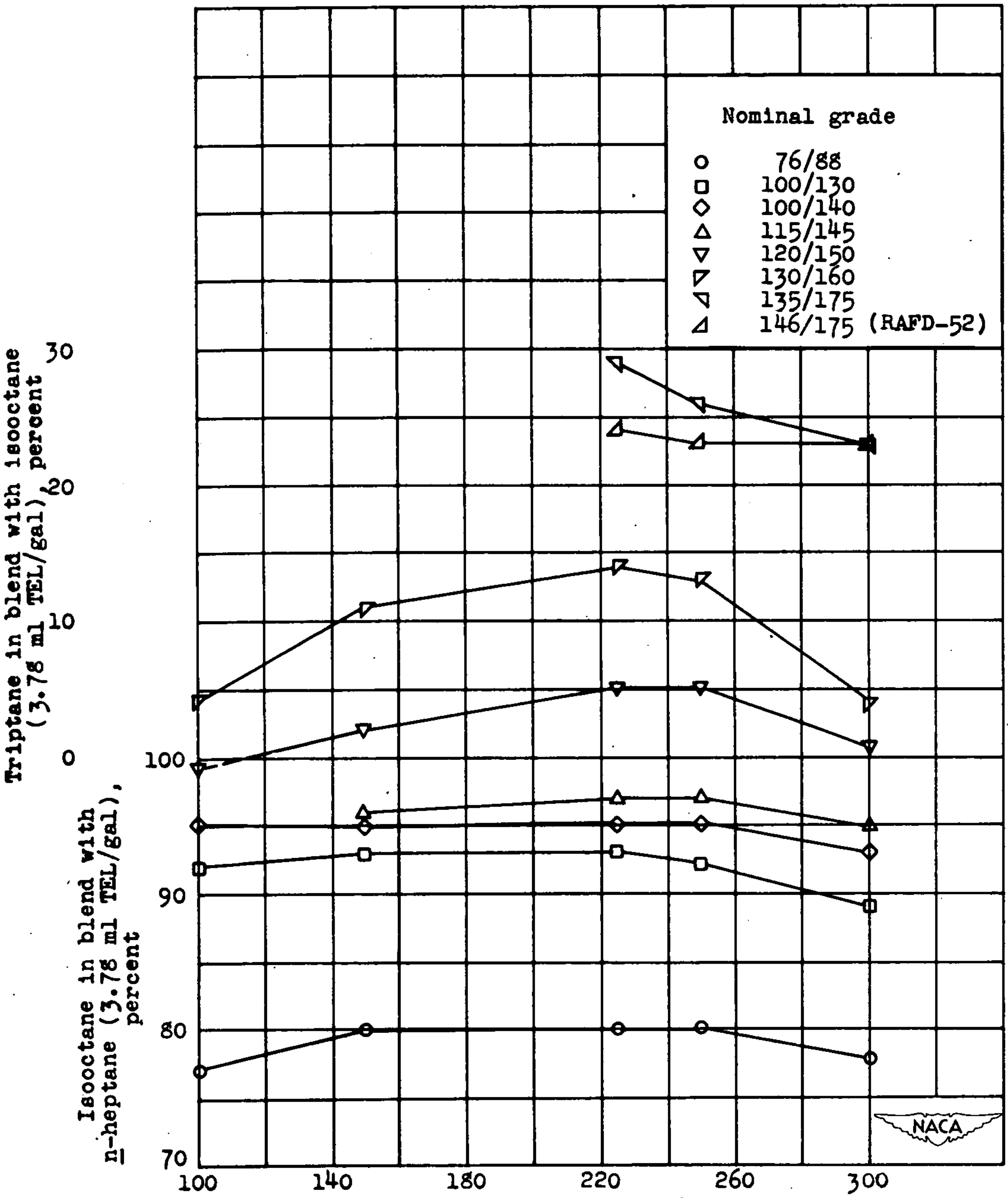
(c) Leaded triptane - n-heptane scale.

Figure 19. - Concluded. Effect of inlet-air temperature on lean (fuel-air ratio, 0.065) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



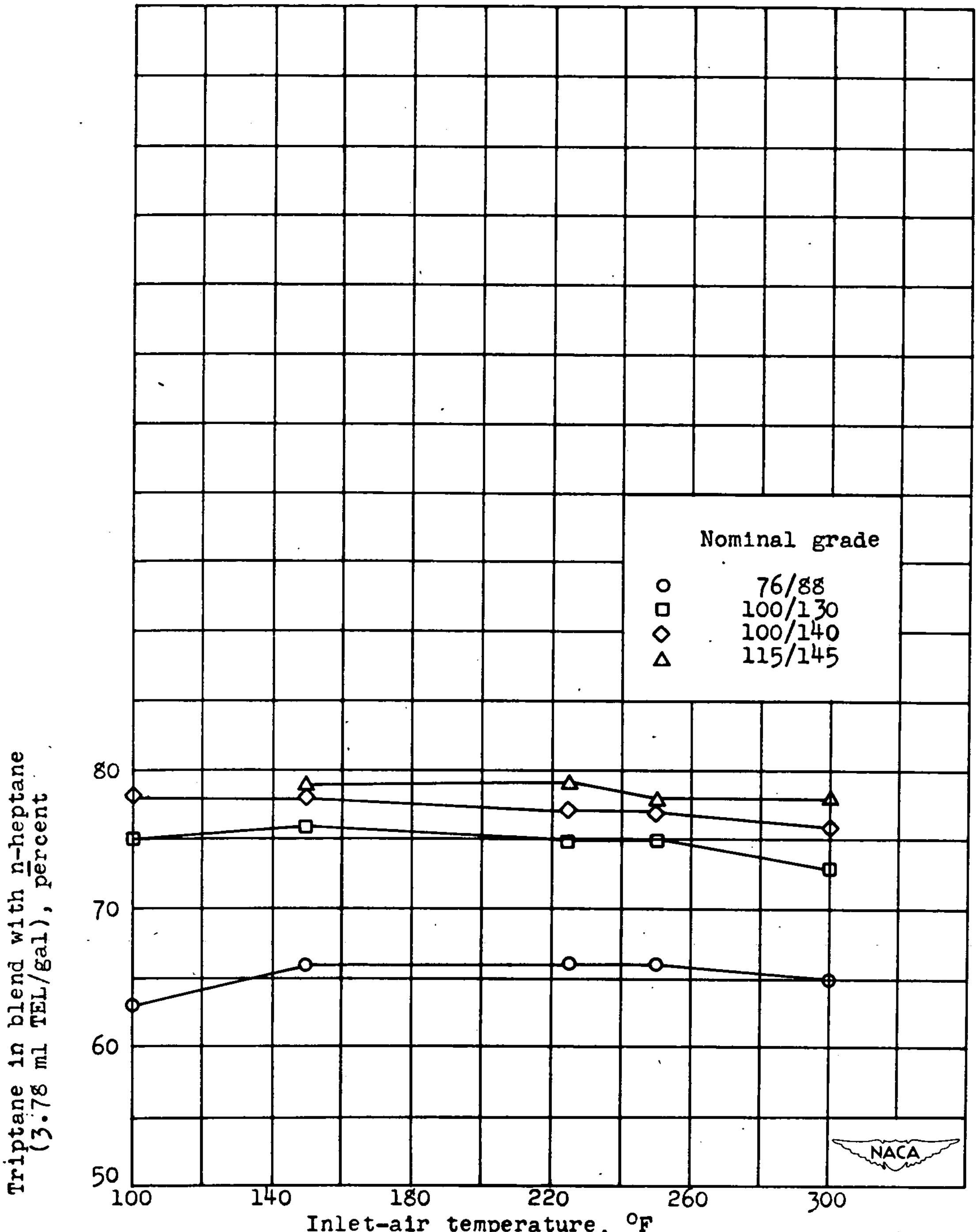
(a) Performance-number scale.

Figure 20. - Effect of inlet-air temperature on rich (fuel-air ratio, 0.11) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



(b) Leaded isooctane - n-heptane and leaded triptane-isooctane scales.

Figure 20. - Continued. Effect of inlet-air temperature on rich (fuel-air ratio, 0.11) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.



(c) Leaded triptane - n-heptane scale.

Figure 20. - Concluded. Effect of inlet-air temperature on rich (fuel-air ratio, 0.11) antiknock ratings assigned from different fuel-rating scales. All conditions other than inlet-air temperature were standard F-4 conditions.

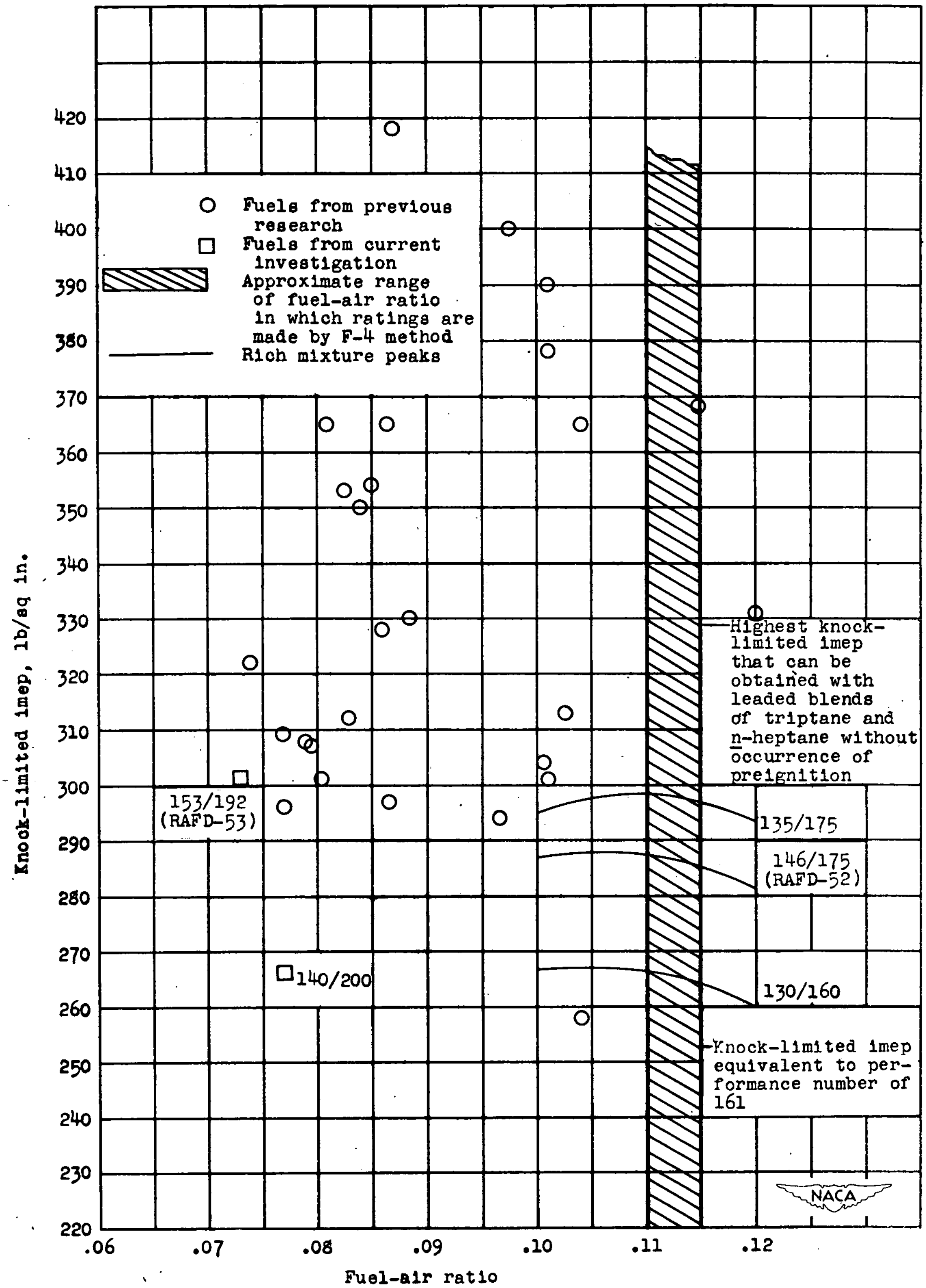


Figure 21. - Maximum knock-limited mean effective pressures that can be obtained for various fuels by F-4 rating method without encountering preignition.